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CANMET
Energy Mines and Resources, Canada

Venturi Gas Scrubbers Employing Molten Salts

Phase I

SNC

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Re: Development, Design and Construction of a Computer Design Model Program of Venturi Gas Scrubber Which Employ Molten Salt

Dear Mr. Marwaha:

We are pleased to submit one (1) original and six (6) copies of the final report for Phase I of the project in accordance with the contract.

We trust this report meets your approval.

Yours truly,

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DEVELOPMENT DESIGN AND CONSTRUCTION
OF
A COMPUTER DESIGN MODEL PROGRAM
OF
VENTURI GAS SCRUBBERS EMPLOYING MOLTEN SALT

REPORT OF PHASE I

BY

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TABLE OF CONTENTS

		Page
	SUMMARY	
	TITLE	
1.0	INTRODUCTION	1
1.1	Objective and Scope	1
1.2	Molten Salt Hot-Gas Scrubbing Process	1
2.0	LITERATURE REVIEW	3
2.1	Background	3
2.2	Modelling and Designing Venturi Scrubbers	3
2.3	Chemistry and Thermodynamics of Molten Carbonates	5
2.4	Design Information and Specifications for Inlet and Outlet Gaseous Streams	6
2.5	Development of the Hot Gas Molten Salt Scrubbing Process	7
3.0	MATHEMATICAL MODEL	9
3.1	General	9
3.2	Assumptions and Approximations	10
3.3	Design Equations	11
3.4	Summary of Mathematical Model	25
3.5	Optimization Procedure	25
3.6	Development of Computer Program	26
4.0	DESIGN OF HOT-GAS SCRUBBING SYSTEM	34
4.1	Process Description	34
4.2	Computer-Optimized Venturi Design	35
4.3	Auxiliary Systems	36

		Page
5.0	PRELIMINARY COST ESTIMATE	40
5.1	Basis of Estimate	40
5.2	Cost of Hot-Gas Scrubbing System	41
5.2.1	Capital Cost	41
5.2.2	Operating Cost	41
5.3	Cost of Cold Gas Scrubbing System	41
5.3.1	Capital Cost	41
5.3.2	Operating Cost	42
6.0	CONCLUSIONS	43
7.0	RECOMMENDATIONS	44
	NOMENCLATURE	45
	BIBLIOGRAPHY	50
	APPENDICES	
	APPENDIX A PHYSICAL AND THERMODYNAMICAL PROPERTIES	
	APPENDIX B EQUILIBRIUM DATA	
	APPENDIX C DESIGN CRITERIA	
	APPENDIX D COMPOSITION OF FUEL GAS FROM IGT U-GAS GASIFIER	
	APPENDIX E SPECIFICATIONS AND DATA FOR EQUIPMENT	
	APPENDIX F COST ESTIMATE	
	APPENDIX G PROCESS DRAWINGS	
	APPENDIX H COMPUTER PROGRAM	

LIST OF FIGURES

	TITLE	PAGE
3.1	Schematic of a Venturi Scrubber	31
3.2	Particle Trajectory Near an Accelerating Drop	32
3.3	Concentration Distribution in a Drop with Chemical Reaction Taking Place at r_o	33
4.1	Plot of Vapor Pressure-Temperature Relationship for NaCl and KCl	39
A.1	Phase Diagram for Na_2CO_3-K_2CO_3-Li_2CO_3 Ternary System	A-9
A.2	Phase Diagram for Na_2CO_3-K_2CO_3-$CaCO_3$ Ternary System	A-10

LIST OF TABLES

	TITLE	PAGE
3-1	Empirical Solution of Equations (1), (2), and (3) for Optimum Value of y_2 [Equation (4)]	27
3-2	Equation (27) - Drag Coefficient as a Function of Reynolds Number	28
3-3	Equation (28) - the Time Taken by a Droplet in Reaching Zero-Relative-Velocity	29
3-4	Equation (29) - the Distance Travelled by a Droplet Before Reaching Zero-Relative-Velocity	30
4-1	Compute-Optimized Venturi Design	39
A-1	Thermochemical Data for the Species Involved in the Molten Salt Scrubbing Process	A-4
A-2	Eutectic Composition, Melting Points, and Heat of Fusion of Some Molten Salt Mixtures (20)	A-7
A-3	Heat of Combustion of Some Product Gases at 298.15° K and 0.1 MPa	A-8
B-1	Equilibrium Constants for the Reaction of Carbonates with Hydrogen Sulfide	B-2
B-2	Thermodynamic Properties for Scrubbing Reactions with Na_2CO_3	B-3

SUMMARY

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A program to optimize the design model was prepared including the most significant design variables. Based on this program, a hot gas scrubbing system has been designed around the optimized venturi design obtained by utilizing the computer model. The study has established that molten salt may be employed to scrub hot dirty gases with considerable saving in energy. A comparative cost estimate of the hot scrubbing system with conventional cold system has been carried out, which has shown that the hot gas scrubbing system is more economical.

It is recommended that a pilot hot-gas venturi scrubber system be constructed for experimental studies and development of a data base which will aid in development of the technology leading to commercialization.

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1.0 INTRODUCTION

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1.1 Objective and Scope

This study was requested by CANMET through the department of Supply and Services, Canada, under contract number 03SQ.23440-1-9099, titled "Development, Design and Construction of a Computer Model Program of Venturi Gas Scrubbers Which Employ Molten Salt - (UP-S-389)".

The work statement required SNC to develop a computer program for simulating and designing venturi scrubbers which employ molten salts. Furthermore, it stated that using the computer program, a set of designs were to be obtained and evaluated for estimating the cost of cleaning hot dirty gases by using molten salts.

1.2 Molten Salt Hot-Gas Scrubbing Process

The molten salt hot-gas scrubbing process was a by-product of the Molten Salt Gasification process developed by M. W. Kellog Company (23). One of the earliest units were tested by Atomics Division of Rockwell International (3, 7), and Battelle Northwest Laboratories (25).

The process essentially employs a venturi to bring into contact dirty hot gases containing particulate and chemical impurities with a mixture of molten salts which acts as scrubbing liquids.

The venturi imparts momentum to the liquid stream which disintegrates into tiny droplets that collect particulate matter by impaction, and sulfurous gases such as H_2S by absorption and chemical reactions. Most of the process developers have used a mixture of molten alkali carbonates as the scrubbing medium.

The gases leaving the venturi enter a de-entrainment unit where the salt droplets are recovered. The salt is regenerated and sent to the feed tank while the hot gases are sent to a turbine to generate electricity.

2.0 LITERATURE REVIEW

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2.1 Background

The relevant literature can be classified in the following four main areas:

1. Modelling and designing venturi scrubbers.
2. Chemistry and thermodynamics of molten carbonates.
3. Design information and specifications for inlet and outlet gaseous streams.
4. Development of the hot gas molten salt scrubbing process.

A brief review of some of the pertinent literature on these areas is presented in the following sections.

2.2 Modelling and Designing Venturi Scrubbers

There are three distinct ways of designing any physical system:

- Theoretical model based on the application of fundamental principles of conservation of mass, momentum, energy, and chemical species along with all the necessary and sufficient assumptions and approximations. The validity of the model is thus dependent on the approximations and assumptions.
- Correlation of dimensionless groups and physico-chemical properties of the system using data generated by experimentation. The applicability of such models is limited by the nature and scope of experiments.
- A combination of both theoretical representation and phenomenological correlations. This approach reduces the degree of uncertainty introduced by approximations and assumptions while increasing the predictability of the model.

Design techniques for any system vary from the plain thumb-rule procedures to sophisticated design schemes involving computer based models.

Some of the more interesting work in the modelling and designing of venturi scrubbers has been done by Calvert (9), Brink and Contant (8), Taheri et al (31), Gnyp et al (16, 17), and Ingebo et al (18, 19).

Calvert (9) carried out force balance on the gas and liquid phases passing through atomizing scrubbers to predict the pressure drop across a scrubber. He also developed an expression predicting particulate collection efficiency of a single liquid droplet travelling through the scrubber. Calvert and co-workers have produced an interesting work outlining some of the design procedures used in scrubber design (10).

Brink and Contant (8) took the experimental approach and correlated the particle collection efficiency to the dimensions of the venturi throat, the diameter and the velocity of the droplets of scrubbing fluid, and the pressure drop across the throat. But, their correlation is not valid for venturi scrubbers of varying size and geometry.

Boll (6) developed a simple mathematical model based on a uniform drop distribution to predict presssure drop and particle collection efficiencies.

Taheri et al (31) used a similar approach but instead of assuming a uniform drop distribution, they used a Gaussian plume distribution and employed one of the family of particle-in-cell techniques to solve the equations predicting particle and drop distribution in the venturi throat.

Gnyp et al (16, 17) used the fundmental mass and momentum conservation principles to study the distribution of liquid droplets in wet collectors. They also carried out experiments to optimize liquid injection in a venturi.

Ingebo evaluated the drag coefficients for liquid droplets in accelerating streams (18). Ingebo and Fisher correlated the distribution of drop sizes in atomized sprays (19).

2.3 Chemistry and Thermodynamics of Molten Alkali Carbonates

Molten carbonate salts act as good reagents for removal of hydrogen sulfide from dirty gases leaving a gasifier or a combustor. Their importance in the present process stems from the fact that they allow scrubbing to take place at a high temperature thus conserving the thermal energy of the gases.

The chemical reactions between hydrogen sulfide and molten carbonate melts have been discussed at length by Cooke et al (11, 12).

Nakamishi (26) has developed a model for predicting the liquidus and eutectic points in molten salt mixtures having a common ion. This correlation can be used in obtaining phase diagrams of higher order systems if experimental data for the binary/ternary systems are available.

The thermodynamic equilibrium for a variety of systems can be predicted by using the Facility for the Analysis of Chemical Thermodynamics (F*A*C*T) programs available from McGill University, Montreal (4). These data are given in Appendix B.

The main sources for obtaining the physical, transport and thermodynamical properties of molten salt mixtures are Janz (20), (Blander (5), Selman et al (30) and the F*A*C*T data banks (4).

Although there is sufficient information for the ternary $(Na\text{-}K\text{-}Li)_2CO_3$, there is a dearth of data for mixtures of alkali carbonates with either calcium carbonate or ferrous carbonate. Appendices A and B give the physical and thermodynamical properties of molten carbonate melts.

2.4 Design Information and Specifications for Inlet and Outlet Gaseous Streams

The scrubbing process is but one of the components of a complete combined cycle power plant. The input to the scrubber consists of hot and dirty gases from the gasifiers while the output from the scrubbing process produces power in a gas turbine. Hence, these units determine the criteria for designing the scrubber.

There is a plethora of data on the products from gasifiers but only a relatively small number of gasifiers have been commercialized. The data used here were obtained from literature on the U-Gas process developed by the Institute of Gas Technology (32). These data are given in Appendix D.

Westinghouse, which is one of the major suppliers of industrial gas turbines, has carried out an extensive study of the effects of hot and dirty gases on turbine internals and turbine operations (32). The design criteria given in Appendix C is based on their work.

One of the more interesting conclusions in the Westinghouse report pertains to the effect of Na and K vapors on the turbine blade material. They concluded that Na and K level in the gas stream should be less than 4 ppb (parts per billion) in order to contain the corrosion of the turbine blades. Thus, the hot gases have to be scrubbed and cleaned to remove particulate matter, sulfur compounds and the NaCl/KCl released from the mineral

matter in coal. Volatile NaCl/KCl are insoluble in the molten carbonate melts. While molten alkali carbonate effectively eliminate particulate and sulfur compounds alternative scrubbing liquids may have to be found or an additional step may have to be introduced in the scrubbing process to eliminate NaCl and KCl. These details are discussed further in later sections.

2.5 Development of the Hot-Gas Molten Salt Scrubbing Process

The hot-gas molten salt scrubbing process has been studied experimentally by Atomics International, a Division of North American Rockwell (3,7), the Battelle Pacific Northwest Laboratories (25), and the Generation Systems Division of Westinghouse Electric Corporation (32). These three studies are reviewed here in brief.

The Atomics International carried out experiments to determine the feasibility of desulfurizing combustion products. It was found that the process was feasible and energy efficient. Their conclusion was that although the process is feasible, its commercialization required further testing and evaluation of various aspects such as the material of construction and the use of other molten salts.

The Westinghouse Electric Corporation has carraied out an extensive investigation of the combined cycle power generation process based on coal gasification. Their efforts were focused on the nature of turbine operation and design problems that may be encountered while generating power from fuel obtained by gasifying coal. They evaluated and compared a hot-gas cleanup system using solids such as limestone, calcined dolomite and iron oxide as sulfur sorbents. The hot-gas sulfur scrubbing system was assumed to be a fixed-bed reactor, while granular filter bed was judged to be the most suitable particulate removal system.

3.0 MATHEMATICAL MODEL

3.0 MATHEMATICAL MODEL

3.1 General

The mathematical model developed here is based on the assumption that experiments will be carried out to obtain the information required for complete description of the scrubbing process.

Figure 3.1 schematically represents the venturi scrubber modelled here.

The scrubbing process can be briefly described as follows:

- Dust and pollutant laden dirty gas enters the venturi-throat and gains momentum.
- Scrubbing liquid is injected near the throat entrance.
- Sprayed liquid atomizes and the droplets accelerate as they travel through venturi.
- During their passage through the venturi, the liquid droplets come into contact with dust particles by impaction, diffusiophoresis and thermophoresis.
- Some of the particles which come into contact with the droplets get entrapped by the droplets.
- Due to their constant contact with the dirty gas, the droplets absorb some of the gaseous pollutants (Diffusion).
- The absorbed pollutants react with the scrubbing reagents and are thus converted to harmless substances. The gas leaving the venturi recovers most of the energy lost due to change in pressure and enters a de-entrainer for removal of liquid droplets.

The above processes can be mathematically represented by a set of equations which describe the trajectory of particles around a droplet, the efficiency of particulate and pollutant collection

by each droplet, the time required by each droplet to reach zero-relative-velocity and the power consumption.

These equations can then be solved simultaneously/sequentially depending upon the nature and relationship between the variables and parameters involved.

The following assumptions and approximations have been made while deriving the equations given in section 3.3.

3.2 Assumptions and Approximations

Some of the important assumptions incorporated in the model are as follows:

- Both the solid particles and the liquid droplets are spherical in shape and there exists a characteristic dimension which can represent their distribution in the venturi. This means that the liquid droplets are formed within a very short distance from the spray nozzles and their distribution is uniform.

- Impaction is the principle particle collection mechanism while diffusion with chemical reaction is the main pollutant removal mechanism.

- The pollutant removal process is diffusion controlled, that is, the chemical reactions are fast and the concentration of gaseous solute inside each of the liquid droplets is given by equilibrium conditions.

- As the pollutant concentration is quite small, the liquid phase can be treated as a dilute solution and Henry's law can be applied at the gas-liquid interface.

3.3 Design Equations

The mathematical mode consists of equations which represent the following main parameters:

1. Particulate trajectory in the vicinity of an accelerating liquid droplet.

2. Particle collection efficiency of each of the individual droplets.

3. Relative velocity of the droplet in the gaseous stream.

4. The time taken by each drop to reach zero-relative-velocity.

5. The distance travelled by a droplet in the time calculated above.

6. The mass balance for particulate material.

7. The balance for pollutant (H_2S absorption and reaction).

8. The coefficient of H_2S absorption and retention.

9. The mass balance on scrubbing liquid.

10. Pressure drop across the venturi.

11. Power consumption.

12. Fixed costs and operating costs.

The nomenclature for the derivation of the equation of streamline in the vicinity of a spherical particle (or drop) is shown in Figure 3.2.

The streamlines around an accelerating drop can be represented by the Milne-Thomson stream function (13),

$$\psi = -0.5\, V_o \sin^2\theta \left(r^2 - \frac{D^3}{8r} \right) \qquad \ldots (1)$$

For a streamline passing through the position 2,

$$\psi \simeq -0.75\, V_o\, D\, y_2 \qquad \text{when } y_2 << D \qquad \ldots (2)$$

Let β, defined as,

$$\beta = \frac{5}{72} \frac{\rho_p d_p^2 V_o C_c}{\mu_g D} \qquad \ldots (3)$$

represent a stream parameter. Then equations (1) and (2) can be solved for the optimum value of the collection distance y_2, by using β as an optimization variable. The results are tabulated in Table 3-1 (equation 4).

The instantaneous particle collection efficiency of any drop is defined by,

$$\eta_{d_i} = \sigma \frac{\pi y_1^2}{\pi D^2/4} \qquad \ldots (4)$$

Substituting for y_1, in the above equation using the continuity equation yields,

$$\eta_{d_i} = \frac{12\sigma}{D^2} \int_0^{y_2} \left(y + \frac{D}{2}\right) \left[\frac{3}{2} \frac{y}{\delta} - \frac{1}{2} \left(\frac{y}{\delta}\right)^3 \right] dy \qquad \ldots (6)$$

Also,

$$\delta = 2.9 \left(\frac{\mu_g D}{\rho_g V_o} \right)^{0.5} \left(\int_0^{\theta_f} \sin^7\theta \, d\theta \right)^{0.5} \qquad \ldots (7)$$

when,

$$\theta_f = \pi/2 \quad , \qquad \delta = \delta_2 \, .$$

Integrating equation (7) and substituting in equation (6) gives the following three equations for particle collection efficiency of each droplet.

When, $y_2 < \delta_2$,

$$\eta_{dp} = 8.811\,\sigma Re_o^{-0.5}\left[\left(\frac{y_2}{\delta_2}\right)^2 - \frac{1}{6}\left(\frac{y_2}{\delta_2}\right)^4 + \frac{4}{3}\frac{\delta_2}{D}\left[\left(\frac{y_2}{\delta_2}\right)^3 - \frac{1}{5}\left(\frac{y_2}{\delta_2}\right)^5\right]\right] \quad \ldots(8)$$

When, $y_2 = \delta_2$,

$$\eta_{di} = 8.811\,\sigma Re_o^{-0.5}\left(\frac{5}{6} + \frac{16}{15}\frac{\delta_2}{D}\right) \quad \ldots(9)$$

and when, $y_2 > \delta_2$,

$$\eta_{di} = 8.811\,\sigma Re_o^{-0.5}\left(\frac{5}{6} + \frac{16}{15}\frac{\delta_2}{D}\right) + 2\sigma\left[\left(\frac{y_2}{D} - \frac{\delta_2}{D}\right)\left(AA + BB + \frac{1}{AA + BB}\right)\right] \quad \ldots(10)$$

where,

$$AA = \frac{2y_2}{D} + 1 \quad \ldots(11a)$$

$$BB = \frac{2\delta_2}{D} + 1 \qquad \ldots (11b)$$

A droplet injected in the gas stream is accelerated by the drag force acting on it such that,

$$\frac{dU}{dt} = \frac{3}{4} C_{DA} \frac{\rho_g}{\rho_l} \frac{(V_g - U)^2}{D} \qquad \ldots (12)$$

where,

$$C_{DA} = C_{D_1} \left(\frac{V_{g_1} - U_1}{V_g - U} \right)^{0.5} \qquad \ldots (13)$$

C_{D1} is the drag coefficient for the droplet at the position 1 (in Figure 3.1).

The droplet velocity, U, is zero at the point of injection and gas velocity at the entrance is generally specified, thus, the boundary condition and the initial condition for equation (12) are,

$$U = 0 \qquad \ldots (14)$$

Let X be the dimensionless distance given by:

$$V_{g_1} = Q_g / A_2 \qquad \ldots (15)$$

Performing necessary transformations, integrating and using the boundary and initial conditions given by equations (14) and (15) yields,

$$U = 2V_g \left(1 - x^2 + x(x^2 - 1)^{0.5}\right) \quad \ldots(17)$$

The relative velocity of the droplet is given by,

$$U_r = V_g - U \quad \ldots(18)$$

In order to determine the time taken by a droplet to reach a given relative velocity, equation (12) is modified,

$$\int_0^t dt = -\frac{4}{3}\frac{\rho_l}{\rho_g} D \int_{U_{r\max}}^{U_r} \frac{dU_r}{C_{DA} U_r^2} \quad \ldots(19)$$

When this equation is employed to determine the travel-time of smaller droplets, the Cunningham correction factor may be incorporated in the drag coefficient. As the drag coefficient is a function of velocity (see Table 3-2), the above equation can be integrated analytically or numerically once an appropriate function is substituted for the drag coefficient.

Let,

$$Re = \frac{U_r \rho_g D}{\mu_g} \quad \ldots(20)$$

$$Re_o = \frac{U_{r\max} \rho_g D}{\mu_g} = \frac{V_g \rho_g D}{\mu_g} \quad \ldots(21)$$

and let, τ, be the dimensionless time defined by,

$$\tau = \frac{t \mu_g}{\rho_l D^2} \quad \ldots(22)$$

Substitution of equations (20) to (22) in equation (19) leads to,

$$\tau = -\frac{4}{3} \int_{Re_o}^{Re} \frac{d(Re)}{C_D Re^2} \qquad \ldots (23)$$

The distance travelled by a droplet before its relative velocity changes from maximum to zero is given by:

$$s = \int_o^t U_r \, dt \qquad \ldots (24)$$

Let, S, be the dimensionless distance defined as,

$$S = \frac{\rho_g S}{\rho_l D} \qquad \ldots (25)$$

Then, substitution of equations (20), (21) and (25) in equation (24) gives,

$$S = \int_{Re_o}^{Re} -\frac{4}{3} \frac{d(Re)}{C_D Re} \qquad \ldots (26)$$

There exists several different empirical equations expressing drag coefficient as a function of Reynolds number. The equations used in present model are given in Table 3-2 [equation (27)]. The integrated forms of equations (23) and (26) are presented in Tables 3-3 and 3-4 respectively. These integrated expressions are labeled equation (28) and equation (29), respectively.

Equations (8), (9) and (10) give the instantaneous particle collection efficiency for any droplet passing through a scrubber. Hence, the total number of particles collected by a single drop during the acceleration period is,

$$\Delta N = \frac{\pi D^2}{4} \sigma C_n \int_0^{S_{max}} \frac{\eta_{di}}{\sigma} \, d(S_{max} - S) \qquad \ldots (30)$$

Therefore, the rate of collection of particles by liquid droplets entering at a rate, $\dot{N}_d$, is equal to:

$$\Delta \dot{N} = -\frac{\pi D^2}{4} C_{nu} \dot{N}_d \sigma \int_0^{S_{max}} \eta_{di} \frac{dS}{\sigma} \qquad \ldots (31)$$

This integral has to be evaluated numerically.

Now,

$$C_{nu} = \frac{\dot{N}}{Q_g} \qquad \ldots (32)$$

$$\eta = \frac{\Delta \dot{N}}{\dot{N}} \qquad \ldots (33)$$

$$Q_l = \frac{\pi D^3}{6} \dot{N}_d \qquad \ldots (34)$$

Substituting equations (26) and (32) to (34) and rearranging changes equation (31) to,

$$F_p = -\frac{\pi}{4} \sum_{S_{min}}^{S_{max}} \eta_{di} \Delta S \qquad \ldots (35)$$

where, F_p, a particle collection function is defined by

$$F_p = \frac{\pi}{6} \frac{\eta \rho_g Q_g}{\sigma \rho_l Q_l} \qquad \ldots (36)$$

In order to obtain a similar function for pollutant removal, consider Figure 3.3 which shows the gas concentration profile near a droplet.

Assuming quasi-steady state, a material balance can be written around a gaseous film surrounding the droplet,

$$\dot{m} = \mathcal{D} A \frac{\partial C}{\partial r} \qquad \ldots (37)$$

The rate of accumulation of any chemical species inside the drop is expressed by,

$$\frac{\partial C}{\partial t} = \frac{\mathcal{D}}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial C}{\partial r} \right) \qquad \ldots (38)$$

The chemical reaction between the pollutant and the reagent may be expressed by,

$$\alpha_1 R_1 + \alpha_2 R_2 \rightleftharpoons \alpha_3 R_3 + \alpha_4 R_4 \qquad \ldots (39)$$

where, 1, denotes the pollutant and, 2, denotes the scrubbing reagent. The reaction is assumed to occur at a reaction front, a radial distance r_o, from the center.

At steady state, equation (38) can be solved analaytically, and the solution can be presented as,

$$C = \frac{Z_1}{r} + Z_2 \qquad \ldots (40)$$

where, Z_1, and Z_2, are variables independent of r. The solution can be applied to both the pollutant and the reagent.

The boundary conditions are,

$$C_1 (r_o, t) = C_2 (r_o, t) = 0 \qquad \ldots (41)$$

$$C_2 (r \leq r_1, i) = C_{2_0} \qquad \ldots (42)$$

and,

$$\frac{\partial C_2}{\partial t}\left(\frac{D}{2}, t\right) = \lambda_1 \left[C_0 - \frac{H M_w}{R_g T \rho_l} C_l \left(\frac{D}{2}, t\right)\right] \quad \ldots (43)$$

where,

$$\lambda_1 = \frac{3}{4} \frac{\mathcal{D}_g}{\delta_l} Sc^{1/3} \left(\frac{V_0 \rho_g}{D \mu_g}\right)^{0.5} \quad \ldots (44)$$

At the reaction front equation (37) gives,

$$\frac{m_1}{m_2} = \frac{\alpha_1 M_1}{\alpha_2 M_2} = \frac{\mathcal{D}_{l_1}}{\mathcal{D}_{l_2}} \left(\frac{-\frac{\partial C_1}{\partial r}(r_0, t)}{\frac{\partial C_2}{\partial r}(r_0, t)}\right) \quad \ldots (45)$$

Now, equation (38) can be solved using the boundry conditions given by equation (41), (42) and (43) to yield an expresion similar to equation (40). Carrying out the necessary mathematical operations and substituting equation (45) in the resultant expression leads to an equation for the rate of pollutant mass transfer,

$$\dot{m}_1 = \frac{4\pi r_1 \mathcal{D}_{l_1} (\lambda_1 C_1 + \lambda_1 \lambda_2 \lambda_3 C_{2_0})}{\frac{4 r_1}{D^2} + \lambda_1 \lambda_3 \left(1 - \frac{2 r_1}{D}\right)} \quad \ldots (46)$$

where,

$$\lambda_2 = \frac{H M_{mix}}{R_g T_l \rho_l} \quad \ldots (47a)$$

$$\lambda_3 = \frac{\alpha_1 M_1 \mathcal{D}_{l_2}}{\alpha_2 M_2 \mathcal{D}_{l_1}} \quad \ldots (47$$

If the scrubbing process is carried out without using a reagent (no chemical reaction), equation (45) changes to,

$$\dot{m}_1' = \frac{4\pi r_1 \lambda_1 C_{1_0} \mathcal{D}_{l_1}}{\frac{4r_1}{D} + \lambda_1 \lambda_3 \left(1 - \frac{2r_1}{D}\right)} \qquad \ldots (48)$$

Let, an attachment parameter be defined as,

$$\sigma = \frac{C_1 - C_{1_0}}{C_{1_0}} \qquad \ldots (49)$$

and, let,

$$\sigma' = \frac{C_1' - C_{1_0}'}{C_{1_0}'} \qquad \ldots (50)$$

then,

$$\frac{\sigma}{\sigma'} = \frac{\dot{m}_1}{\dot{m}_1'} \qquad \ldots (51)$$

Substitution of equations (46) and (48) in equation (51) results in,

$$\frac{\sigma}{\sigma'} = 1 + \lambda_2 \lambda_3 \frac{C_{2_0}}{C_{1_0}} \qquad \ldots (52)$$

Now, the efficiency of collecting the pollutants is defined as,

$$\eta_d = \frac{4\dot{m}_1}{\pi D^2 V_0 C_{1_0}} \qquad \ldots (53)$$

which can also be written as,

$$\eta_d = \frac{3\sigma}{Sc^{2/3} Re^{0.5}} \qquad \ldots (54)$$

In the absence of a reacting medium, equation (43) can be solved

to yield,

$$\frac{C_{l_1}}{C_{Hl_1}} = \frac{\lambda_4 + \phi(F_0)\,\mathcal{B}_{l_1}[C_{l_1\ell}/C_0]}{\lambda_4 + \phi(F_0)\,\mathcal{B}_{l_1}/\lambda_2} \quad \ldots (55)$$

where,

$$\lambda_4 = \mathcal{B}_{g_1}\, Sc^{1/3}\, Re^{1/2} \quad \ldots (56)$$

$$F_0 = \frac{\mathcal{B}_{l_1} t}{D^2} \quad \ldots (57)$$

and,

$$\phi(F_0) = 5.32 \sum_{n=1}^{\infty} \exp(-4\pi n^2 F_0) \quad \ldots (58)$$

Substituting equation (55) in equation (50),

$$\sigma' = 1 - C_{l_1}/C_{Hl_1} \quad \ldots (59)$$

Thus, using equations (52), (54), (55) and (59), the efficiency of pollutant collection can be obtained when a reagent is employed for chemical conversion of the pollutant.

The continuity equation gives,

$$\Delta m = -\frac{\pi}{4} D^2 C_0 \sigma \int_0^{s_{max}} \frac{\eta_d}{\sigma}\, d(s_{max} - s) \quad \ldots (60)$$

Thereby, similar to the case for particle collection,

$$F_g = -\frac{3\pi}{4} \sum_s \frac{\Delta S}{Re^{0.5}} \quad \ldots (61)$$

where, F_g is a pollutant collection function defined by,

$$F_g = \frac{\pi \eta \rho_g Q_g Sc^{2/3}}{6 \rho_l Q_l} \qquad \ldots (62)$$

The particle and pollutant collection functions F_p and F_g defined by equations (36) and (62) can be used to determine the respective collection efficiencies or the liquid flow rates required for achieving specified collection efficiencies. In the later case, the larger of the two liquid flow rates should be used for determining the pressure drop and operational costs.

The pressure drop across a venturi and the power consumed loss are given by

$$\Delta P = \left(\frac{P_1 - P_4}{P_1 - P_2}\right)(P_1 - P_2) + \frac{Q_l}{Q_g} \rho_l V_2^2 \qquad \ldots (63)$$

$$E = \Delta P * Q_g \qquad \ldots (64)$$

The ratio of total pressure, (P_1-P_4), to the inlet-throat pressure drop, (P_1-P_2), is obtained from graphs available in the literature (13).

Depending upon whether the gas flow is compressible or incompressible, the pressure differential, (P_1-P_2), is given by equations (65) and (66) respectively.

$$P_1 - P_2 = 0.515 \rho_{g_1} V_1^2 \left[(A_1/A_2)^2 - 1\right] \qquad \ldots (65a)$$

$$\left(\frac{P_2}{P_1}\right)^{2/k}\left[1+\frac{\rho_{g,1}V_1^2}{P_1}\frac{(k-1)}{2kC_c^2}\right]-\left(\frac{P_2}{P_1}\right)^{1+1/k}=\frac{(k-1)\rho_{g,1}V_1^2}{2kC_c^2P_1}\left(\frac{A_1}{A_2}\right)^2 \quad \cdots(65b)$$

A trial and error procedure has to be used to determine, (P_1-P_2), when the gas flow is compressible.

In addition to the above equations, the following equations are required to complete the mathematical model.

The diameter of liquid droplets is obtained by the frequently used Nukiyama-Tanasawa equation (22):

$$D=\frac{0.585}{U_r}\left(\frac{\sigma_s}{\rho_l}\right)^{0.5}+597\times10^{-1.05}\left(\frac{\mu_l}{\sigma_s\rho_l}\right)^{0.45}\left(\frac{Q_l}{Q_g}\right)^{1.5} \quad \cdots(66)$$

This equation is used with some reservations because it has been found to be accurate only for a certin range of gas velocities (6, 10, 16). This defect exists in many of the alternative equations too, and therefore, this simple equation has been used rather widely. For example, Ingebo and Foster (19) have developed an expression for the volume mean diameter and the maximum diameter of a drop in atomized sprays. Their equation is quite useful when predicting the performance of an existing atomizing system because it is based on the orifice diameter of the spray nozzles. One of the main reasons why it has not been used quite extensively in design calculations is that such engineering details as the number and size of spray nozzle are available only after a venturi has been sized.

It should be noted that the equation for particle collection efficiency (equation (35)) is based on the Sauter mean diameter while the equation for pollutant removal efficiency uses a "size

average" diameter. These two are related to each other by the droplet size distribution function which has to be obtained experimentally.

The Sauter mean diameter is defined as,

$$D_{1,2} = \frac{\int_0^1 d_{p_i}^3 \, dF}{\int_0^1 d_{p_i}^2 \, dF} \qquad \ldots (67)$$

where, F is the cummulative relative frequency of particles of size d_{pi}.

The "size average" diameter is defined as,

$$D_{1,0} = \int_0^1 d_{p_i} \, dF \qquad \ldots (68)$$

The subscripts on these diameters correspond, respectively, to the standard notations for moment distribution factor, and the weighing factor.

The Cuningham correction factor for drag coefficients is given by,

$$C_c = 1 + \frac{2\lambda}{d_p}\left[1.257 + 0.4 \exp\left(-1.1 \frac{d_p}{2\lambda}\right)\right] \ldots (69)$$

where, λ, is the mean free path,

$$\lambda = \frac{\mu_g}{0.499 \rho_g \bar{u}} \qquad \ldots (70)$$

In the above equation, the mean molecular velocity $\bar{u}$, according

to the kinetic theory of gases is,

$$\bar{u} = \left(\frac{8 R_g T_g}{\pi \, M_{w_g}} \right)^{0.5} \qquad \ldots (71)$$

3.4 Summary of Mathematical Model

The set of design equations constituting a mathematical model of a venturi scrubber comprises of equations (4), (8-10), (17), (27-29), (35), (52), (54), (59), (61), (63-67) and equation (69).

3.5 Optimization Procedure

The Hook and Jeeves design procedure has been selected to optimize the venturi design. This procedure is fairly widely used for such purposes and the details are not presented in this report.

The total cost [equation (72)] and the H_2S removal efficiency have been selected as the objective functions.

The total yearly cost of the venturi is given by,

TOTAL COST = ANNUAL CAPITAL COST + FIXED COST + ANNUAL OPERATING COST ...(72)

The ANNUAL CAPITAL COST is the interest on investments, taxes, and insurance charges. The FIXED COST is the depreciation charges for the capital invested in putting up the system, i.e. scrubber F.O.B. cost, cost of auxiliaries and installation charges. The ANNUAL OPERATING COST includes the cost of energy, the cost of fresh salts, the cost of regenerating the salts, maintenance charges, labour and overhead charges. This is given by

$$OC = \$NT + HR \frac{\$E}{3.6 \times 10^6} \left[\frac{Q_g \Delta P}{\eta_p} + \frac{Q_l}{\eta_f} \left(\Delta P_f + \rho_l g_o h \right) + f \rho_l Q_l \frac{\$L}{\$E} \right] + \$HE \quad \ldots (73)$$

The annual capital cost and fixed costs can be expressed in terms of bulk weight of the venturi, thus, this cost factor suggests the throat area, throat length, and the ratio of entrance to throat area as possible optimization variables. A lowering or minimization of the fixed and capital cost will only be achieved when the total surface area (or bulk weight) of the venturi reaches a minimum.

The operating cost is a function of the pressure drop across venturi, and the amount of liquid flowing through the system. This suggests the use of the liquid flow rate Q_l, as a design variable.

The efficiency of pollutant removal is related directly to the liquid flow rate, and indirectly to the dimensions of the venturi. Therefore, the same variables can be used while optimizing the collection efficiency.

3.6 Development of Computer Program

The mathematical model as well as the cost function and optimization procedure were transformed into a computer program in FORTRAN IV (G Compiler). This program is given in Appendix H.

TABLE 3-1

EMPIRICAL SOLUTION OF EQUATIONS (1), (2) and (3)
FOR OPTIMUM VALUE OF y_2 (EQUATION (4))

RANGE	EXPRESSION
$0 < \beta \leq 0.01$	$\frac{y_2}{D} = \frac{2\beta(1 - 2\beta^{1/3})^{4/3}}{(1 + \beta^{1/3})^{1/3}} + 2.543 \times 10^{37} \exp - \left(\frac{85.705}{\beta^{0.01625}}\right)$
$0.01 \leq \beta \leq 0.6$	$\frac{y_2}{D} = \exp - \left(\frac{2.352}{\beta^{0.1422}}\right) + 0.03128 \sin 0.15112(\ln \beta + 4.6052)^{1.661}$ $- 0.00331 \sin 0.6538(\ln \beta + 4.6052)^{1.1136}$
$0.6 \leq \beta \leq 5$	$\frac{y_2}{D} = \exp \left(- \frac{2.352}{\beta^{0.1422}}\right) + 0.03128 \sin 0.15112(\ln B + 4.6052)^{1.661}$
$\beta \geq 5$	$\frac{y_2}{D} = 0.1665 - 0.235 \exp (-1.8964\beta^{0.2694})$

TABLE 3-2

EQUATION (27)

DRAG COEFFICIENT AS A FUNCTION OF REYNOLDS NUMBER (REFERENCE 22)

RANGE	EXPRESSION
$0 < Re \leq 0.1$	$C_D = 24/Re$
$0.1 < Re \leq 0.5$	$C_D = 24/Re + 4.5$
$0.5 < Re < 3.0$ $400 < Re < 800$	$C_D = 24/Re + 3.60/Re^{0.313}$
$3.0 \leq Re \leq 400$	$C_D = 24/Re + 4/(Re)^{1/3}$
$800 \leq Re \leq 3000$	$C_D = 0.22 + 24(1 + 0.15\ Re^{0.6})/Re$

TABLE 3-3

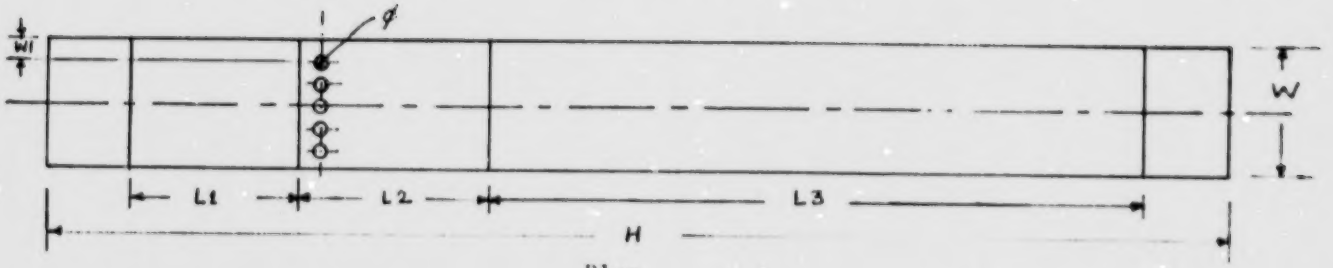
EQUATION (28)
THE TIME TAKEN BY A DROPLET IN REACHING ZERO-RELATIVE-VELOCITY

RANGE	EXPRESSION
$0 \leq Re \leq Re_o < 0.1$	$S_1 = (Re_o - Re)/18$
$0.1 \leq Re \leq Re_o < 0.5$	$S_2 = \frac{4}{13.5} \ln \left[\frac{16 + 3\,Re_o}{16 + 3\,Re}\right]$
$0.5 \leq Re \leq Re_o < 3.0$	$S_3 = 3.0709088 \left[x_o - x + \tan^{-1} x - \tan^{-1} x_o\right]$ where, $x = \sqrt{0.15}\ Re^{0\ 3435}$
$3 \leq Re \leq Re_o < 400$	$S_4 = \sqrt{6} \left[x_o - x + \tan^{-1} x - \tan^{-1} x_o\right]$ where, $x = \frac{Re^{1/3}}{\sqrt{6}}$
$400 \leq Re \leq Re_o < 800$	$S_5 = S_3$

TABLE 3-4

EQUATION (29)
THE DISTANCE TRAVELLED BY A DROPLET BEFORE REACHING ZERO-RELATIVE-VELOCITY

RANGE	EXPRESSION
$0 < Re \leq Re_o < 0.1$	$\zeta_1 = \frac{1}{18} \left(\ln \frac{Re_o}{Re} \right)$
$0.1 \leq Re \leq Re_o < 0.5$	$\zeta_2 = \frac{1}{18} \ln \left[\frac{3 + 16/Re}{3 + 16/Re_o} \right]$
$0.5 \leq Re \leq Re_o < 3.0$	$\zeta_3 = \frac{1}{18} \ln \left[\frac{3 + 20\ Re^{-0.687}}{3 + 20\ Re_o^{-0.687}} \right]$
$3.0 \leq Re \leq Re_o < 400$	$\zeta_4 = \frac{1}{6} \ln \left[\frac{1 + 6\ Re^{-1/3}}{1 + 6\ Re_o^{-1/3}} \right]$
$400 \leq Re \leq Re_o < 800$	$\zeta_5 = \zeta_3$



Plan

Elevation

Figure 3.1 Schematic of a Venturi Scrubber.

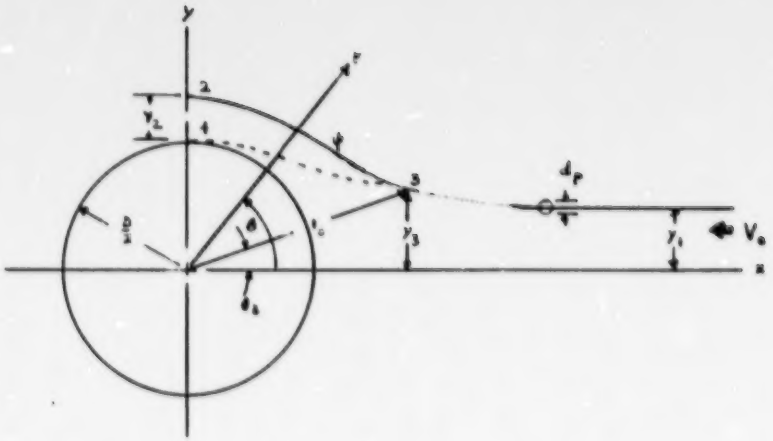


Figure 3.2 Particle Trajectory Near An Accelerating Drop.

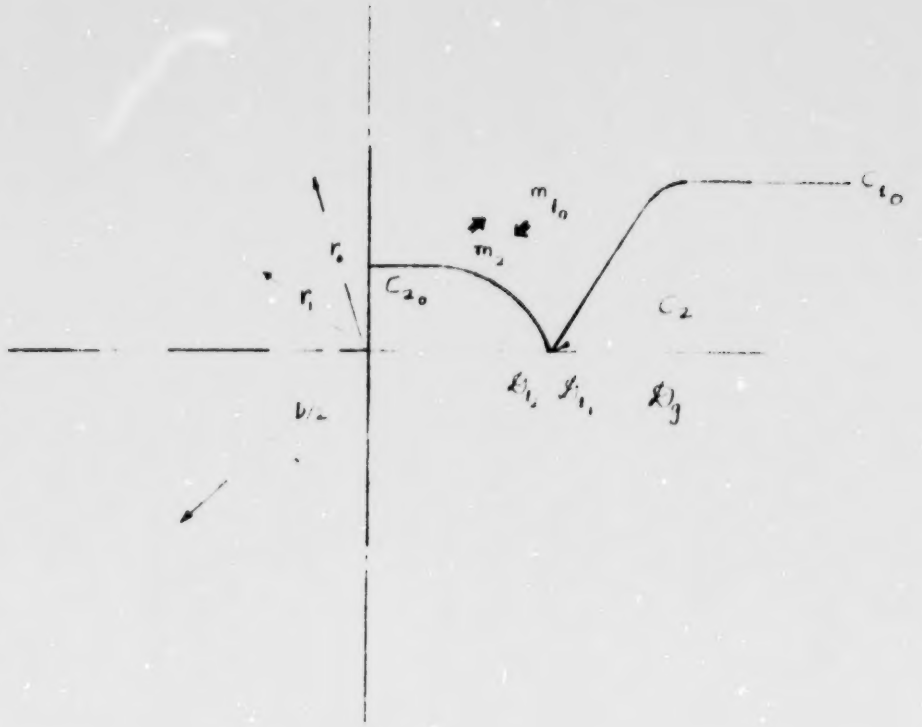


Figure 3.3 Concentration Distribution in a Drop With Chemical Reaction Taking Place at the Reaction Front at r_0.

4.0 DESIGN OF HOT-GAS SCRUBBING SYSTEM

4.0 DESIGN OF HOT-GAS SCRUBBING SYSTEM

4.1 Process Description

The hot-gas scrubbing system developed here is based on the principles outlined earlier in this report. The heart of this scrubbing process is a venturi gas scrubber which employs molten salts to remove the sulfurous pollutants from hot gases produced by gasification or combustion.

The various chemical reactions occuring between the gaseous pollutants and the molten salts are given in Appendix B.

The process is shown in Drawing No. 6615-49DD-0001-PA. The IGT U-Gas coal gasifier has been selected as representative commercial gasifier. The composition and conditions of the gases produced by an IGT U-Gas coal gasifier are given in Appendix D. The gases coming from such a gasifier are passed through a series of cyclones to remove char and ash particles larger than 100 m. The gases at such high temperatures may be scrubbed directly with a molten carbonate mixture and the thermal energy of these gases may be used to generate power from gas turbine if the gas stream meets the turbine requirements. These requirements are given in Appendix C and they constitute the design criteria for the scrubbing system.

In most instances, when coal is gasified, the gaseous stream contains KCl and NaCl in vapor and ionic form and their concentration depends upon gasification conditions. The IGT U-Gas process generates fuel gases at about 1000°C and 0.1 MPa. This gas contains 75 ppm of KCl and 59 ppm of NaCl. After reviewing several alternatives, it has been decided to use the proven and the simplest alternative, namely, cooling the gses to a temperature at which the vapor pressures of KCl and NaCl are less than

the allowable partial pressures of 4 parts per billion by volume (ppb). From Figure 4.1, it can be seen that this condition is satisfied at a temperature below 550°C.

The process includes a bank of heat exchangers-economizers which recover the energy of the hot dirty gases by direct heat transfer to the colder but clean gas.

The dirty gas enters the venturi at a temperature of 550°C. There, it comes in contact with the scrubbing liquid - a mixture of Na_2CO_3-Li_2CO_3-K_2CO_3-$CaCO_3$/F_eCO_3. The molten salt is injected near the throat entrance and it atomizes upon impact with the gas stream. The gas leaving the venturi enters a conical separator where most of the liquid is recovered by centrifugal force. The remaining amount of liquid exists in the form of mist and is recovered in a knock-out drum. The cold clean gas leaving the knock-out drum passes through the bank of heat exchangers and heats up to a temperature of about 650-675°C.

The recovered liquid is returned to the molten salt furnace while a bleed stream is diverted to the salt regeneration system.

A salt make-up tank is also included in the system.

The venturi scrubber forms the core of the process and the rest of the system may be considered as auxiliary units. Thus, it is necessaary to optimize the design of the venturi scrubber.

4.2 Computer - Optimized Venturi Design

The mathematical model developed in Section 3.0 was converted to a computer program and the Hook and Jeeves optimization procedure was utilized in optimizing the venturi design.

The input to the computer program consists of physical and thermodynamical properties of both the gas and the liquid streams, chemical composition of each of the streams, transport properties and an initial guess for the design variables. The design variables used in present model are the dimensions of venturi and the liquid flow rate (see Section 3-5). A set of constraints for the design variables, a set of step sizes for the optimization variables and the defining parameters of the cost equation (objective function) are also needed.

Upon using the input values given in Appendices A to D, several venturi designs were obtained. As the venturi is operated at a temperature of about 550°C, the selected material of construction is aluminized 304L stainless steel. The venturi is internally lined with stellite 6B to protect the equipment from errosion and corrosion. The details of venturi selected here are shown in Drawing No. 6615-45DD-0001-PA.

Based on a gas flow rate of 44.2 kg/s (110 m^3/S @ 550°C, 0.1 MPa) 0.79 litres of molten salts are required per cubic meter of gas flowing through the throat. This liquid flow rate gives a particulate removal efficiency of 99.9999% and a H_2S removal efficiency of 98.7%. Approximately 6600 kilograms of fresh salt mixture is required every hour. The energy required to melt this amount of solids is obtained electrically. This amounts to 4.0 MW.

4.3 Auxiliary Systems

The auxiliary system consists of the bank of heat exchangers, the conical separator, the knock-out drum, the molten salt furnace, the salt make-up drum and the acid-egg pumps required to pump the molten salts up to the venturi throat (see Drawing No. 6625-49DD-0001-PA).

The conical separator measures 6.8 m at the top and 10.8 m at the bottom. Its height is 14.0 m.

Four outside-packed floating head, type AEP, shell and tube heat exchangers are used in parallel to cool the hot dirty gas from 1000°C to 550°C at 0.1 MPa. Each of the heat exchangers provides a heat transfer area of 560 m^2. The shell diameter is 1.2192 m and 2242 tubes of 1.905 cm O.D. x 6.096 m long arranged in a triangular pitch of 2.38 cm are needed to obtain required area. The hot dirty gases are passed on the tube side so that the shell is not fouled by the particulate matter and condensing KCl/NaCl. Periodic cleaning of the tubes will be required. The tube bundle can be changed more easily and at a lower cost. The tubes may be made from special metals such as IN-671 or IN-800.

The knock-out drum measures 5.0 m I.D. x 12.0 m high. It is made from aluminized 304L stainless steel.

The acid egg pumps have a capacity of 4.5 m^3 each. Three such units are required.

The salts are melted in a 7 m^3 volume electric furnace providing 4.0 MW.

The salt make-up drum is a 2.5 m^3, 2.0 MW unit. It is also made from 304L stainless steel.

TABLE 4-1

COMPUTER - OPTIMIZED VENTURI DESIGN

Throat Area, m^2	1.1175
Throat Length, m	3.0000
Divergent Angle	7.0
Convergent Angle	15.0
Inlet Area/Throat Area	3.8133
Total Length, m	11.57
Liquid flow, l/m^3 of gas	0.77

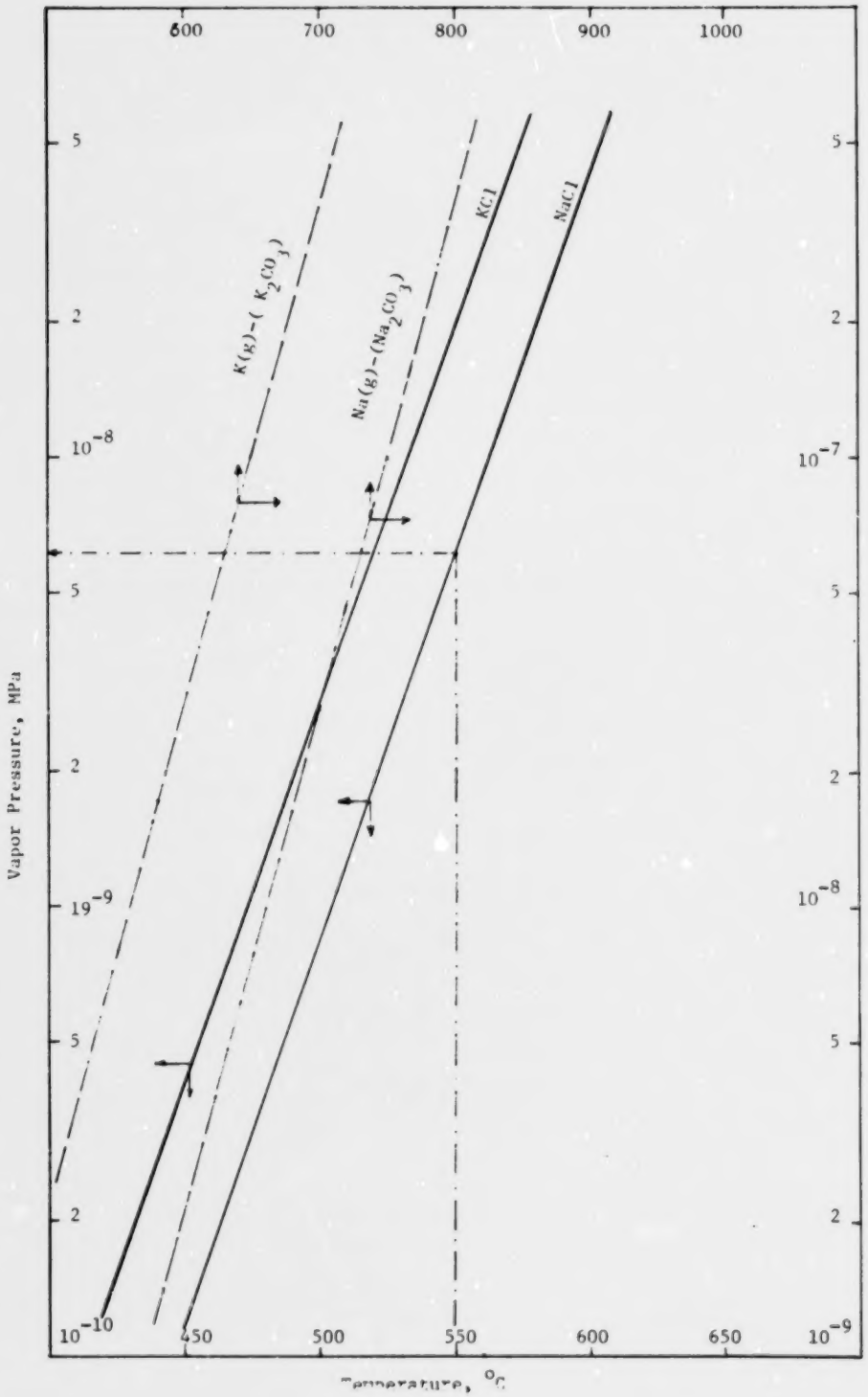


Figure 4.1 Plot Vapor of Pressure-Temperature Relationship for NaCl, KCl.

5.0 PRELIMINARY COST ESTIMATE

5.0 PRELIMINARY COST ESTIMATE

5.1 Basis of Estimate

This is a preliminary cost estimate for the hot-gas venturi scrubber and auxiliary sytem employing molten carbonate salts.

The estimate includes the sitework, the erection cost including the foundations, structural steel, mechanical and electrical services, the process equipment and associated civil, electrical and automation works.

The estimate is based on the following drawing:

- Hot-Gas Scrubbing System Drawing No. 6521-49DD-001 Rev. PA.

Costs shown under the "Labor" columns are subcontractor rates including wages, burdens, fringe benefits, field supervision, temporary facilities, small tools, equipment rental, home office cost and profit. The hourly labor rate has been fixed at $40.00 and it is based on 40-hours week.

Cost shown under the "Permanent Equipment" column include cost of major equipment F.O.B. Equipment prices were obtained from budget telephone quotations and in-house data.

Costs shown under the "Subcontractor" column include all labor, material, subcontractor indirect cost, overhead and profit.

The validity base date of this estimate is May 1983. It reflects all wage rates, material and equipment price as of May 1983.

An overall contingency of 15% has been included. This contingency provides allowance for elements of costs within the defined scope of this estimate that can not be explicitly foreseen or

described, at the time the estimate was made, because of the lack of complete, accurate and detailed information. It specifically excludes any change of order or change of scope.

The accuracy of this preliminary estimate is + 20%.

5.2 Cost of Hot-Gas Scrubbing System

5.2.1 Capital Cost

The preliminary estimate of the cost for the hot-gas venturi scrubbing system employing molten salts is $23,140,000 including 15% for contingencies. The estimated total cost does not include any SNC service charges. The details of the estimate are given in Appendix F.

5.2.2 Operating Cost

The estimated operating cost for the hot-gas scrubbing system are $3,000,000 per annum. This includes such cost items as labor, material, overhead services and utilities, maintenance, interests, rental charges, taxes and capital charges.

5.3 Cost of Cold-Gas Scrubbing System

5.3.1 Capital Costs

The capital cost of a conventional cold-gas scrubbing system using Selexol process (Drawing No. 6615-0002, Rev. PA) is estimated to be $210,382,000 including 15% for contingencies. The estimated cost does not include any service charges or fee. The details of the estimate are given in Appendix D.

5.3.2 Operating Cost

The operating cost of the cold-gas scrubbing system is $2,500,000 per annum. This includes the various cost items discussed in Section 5.2.2.

6.0 CONCLUSIONS

6.0 CONCLUSIONS

This study has established that molten salts may be employed to scrub hot dirty gases with considerable savings in energy.

From the feasibility analysis carried out during Phase I of this program it is concluded that the computer program developed here can be used to simulate and design venturi scrubbers which employ molten salts. It is further concluded that the design presented in Section 4.0 meets the design criteria given in Appendix C, and it is of practical dimensions, thus it can be constructed for development work.

A simple but proven solution has been adopted for the removal of KCl and NaCl which critically affect the performance of gas turbines.

Upon comparing the hot-gas scrubbing system with a conventional cold-gas scrubbing system, it is evident that the hot-scrubbing system is more economical.

7.0 RECOMMENDATIONS

7.0 RECOMMENDATIONS

The hot-gas venturi scrubbing system employing molten carbonates appears to be a promising energy-efficient and economical alternative. Based on the conclusions made in the previous section, it is recommended that a pilot hot-gas venturi scrubber system be constructed for experimental studies and development of a data base which will aid in development of the technology leading to commercialization.

Regarding the operation of such an unit it is recommended that the hot-gas venturi scrubber should be operated at a temperature around 550°C so that the amount of KCl and NaCl in the exit stream do not exceed the limits set by turbine manufacturers.

It should be noted the cost comparison between the hot-gas and cold-gas systems are approximate because the design of both the systems is conceptual. Further comparison can be made more meaningful by carrying out detailed design of a pilot hot-gas scrubbing facility which will allow more exact estimates of the equipment costs. Hence, the next step in this program of developing hot-gas scrubbing system should be detailed engineering, and cost estimate including vendor quotations.

NOMENCLATURE

NOMENCLATURE

Roman Symbols

A - Area, equation 37, m^2.

A_1 - Area, m^2.

A_2 - Area, m^2.

AA - Dimensionless parameter, equation 11a.

BB - Dimensionless parameter, equation 11b

Br - Breadth of throat section, m

C - Concentration, mol% or kg/m^3 or $kgmole/m^3$

C_c - Cunningham correction factor, dimensionless.

C_D - Drag coefficient, dimensionless

C_{DA} - Drag coefficient, equation 13, dimensionless

C_{D1} - Drag coefficient at the point of liquid injection, dimensionless.

C_{HL1} - Concentration of pollutant in liquid phase at equilibrium condition, kg/m^3 or $kgmole/m^3$.

C_l - Concentration in liquid phase, equation 43, kg/m^3 or $kgmole/m^3$

C_n - Concentration of particles, number/m^3.

C_o - Concentration in free gas stream, kg/m^3 or $kgmole/m^3$.

C_1 - Concentration of pollutant, equation 41, kg/m^3 or $kgmole/m^3$.

C_2 - Concentration of reactant (liquid), equation 42, kg/m^3 or $kgmole/m^3$.

D - Droplet diameter, m.

$D_{1,2}$ - Sauter mean diameter, equation 67, m.

d_p - Diameter of particles, m.

E - Energy, J.

F_g - Pollutant collection function, equation 62.

F_o - Fourier number, equation 57, dimensionless.

F_p - Particle collection function, equation 36.

f - Amount of make-up salts, dimensionless.

g. - Gravitalional acceleration, m/s^2.

H - Henry's law constsnt, mole%/MPa.

HR - Number of operational hours per year.

h - Height of venturi scrubber, m.

NOMENCLATURE (cont'd)

Roman Symbols (cont'd)

r_o - Radius of reaction front, figure 3, m.
S - Dimensionless distance, equation 25.
Sc - Schmidt number, $\mu/\rho D$, dimensionless.
s - Distance from injection point, m.
T - Temperature, ^oC or K.
T_c - Critical temperature, ^oC or ^oK.
TC - Total yearly cost, $/y.
t - Time, s.
U - Droplet velocity, m/s.
U_r - Drop velocity relative to gas stream, m/s.
U_{rmax} - Relative velocity of drop, maximum, m/s.
$\bar{u}$ - Mean, molecular velocity, equation 71, m/s.
$\tilde{V}_g$ - Gas velocity, m/s
V_o - Velocity of free gas stream at the inlet, m/s.
V_g - Molar volume of gaseous solute, equation A.8, $cm^3/gmole$.
W - Width of venturi, m.
X - Dimensionless parameter, equation 16.
x - Distance from throat entrance, m.
X_i - Mole fraction of gaseous species i, mole/mole.
y_2 - Collection distance (Figure 3.2), m.
Z_1, Z_2 - Coefficients defined by equation 40.

Special Characters

$E - Energy cost, equation 73, $/kWh.
$HE - Cost of heating and melting salts, $/kg.
$L - Cost of salt mixture, $/kg.
$MT - Maintenance cost, $/y.
$\mathcal{D}_{gi}$ - Diffusivity of species i in gaseous mixture, m^2/s.
$\mathcal{D}_{\ell i}$ - Diffusivity of species i in liquid phase, m^2/s.

NOMENCLATURE (cont'd)

Roman Symbols (cont'd)

K - Boltzman constant, 1.38048×10^{-23} J/molecule ^{o}K

k - Ratio of specific heat at constant pressure to specific heat at constant volume, dimensionless.

L - Length, m

M_i - Molecular weight of species i, kg/kg mole.

M_w - Molecular weight of solvent, kg/kgmole.

M_1 - Molecular weight of pollutant, kg/kgmole.

M_2 - Molecular weight of reagent, kg/kgmole.

$\dot{m}$ - Mass flow rate, kg/s

$\dot{m}'$ - Rate of mass transfer in the absence of chemical reaction, kg/s.

$\dot{N}_d$ - Rate of injection of liquid droplets, number/s.

ΔN - Total number of particles collected by a drop.

Δ_N - Rate of collection of particles, number/s.

n - Parameter, (1, OC), equation 58, dimensionless.

OC - Operating cost, $/Y.

P - Pressure, Pa.

ΔP - Pressure drop, Pa.

ΔP_f - Feed pressure for liquid stream, Pa.

Q_g - Gas flow rate, m^3/s.

Q_ℓ - Scrubbing liquid flow rate, m^3/s.

R_g - Gas constant, J/kgmole-^{o}K.

Re - Reynolds number, dimensionless.

Re_p - Reynolds number based on particle or droplet diameter, dimensionless.

Re_o - Reynolds number at the entrance to the venturi or the liquid injection point depending upon the equation, particle or droplet diameter, gas velocity or relative velocity of drop etc., dimensionless.

r - Radial distance from the center of a liquid droplet, m.

NOMENCLATURE (cont'd)

Greek Symbols

α - Stoichiometric coefficients for chemical reaction, dimensionless.

β - Stream parameter, equation 3, dimensionless.

γ_1 - Association parameter for liquid phase, equation A.8.

δ - Boundary layer thickness around a sphere, equation 7, m.

ϵ - Characteristic energy of molecular interaction, J.

η - Efficiency, dimensionless.

η_d - Pollution collection efficiency, equation 53, dimensionless.

η_{dl} - Instantaneous collection efficiency of droplet of given diameter, equation 5, dimensionless.

η_f - Fan efficiency, dimensionless.

η_p - Pump efficiency, dimensionless.

θ - Angle, Degrees or Radiant.

λ - Mean free path, equation 66, m.

λ_1 - Parameter defined by equation 44.

λ_2 - Parameter defined by equation 47a.

λ_3 - Parameter defined by equation 47b.

λ_4 - Parameter defined by equation 56.

μ_g - Viscosity of gas, kg/m-s.

μ_L - Viscosity of scrubbing liquid, kg/m-s.

π - 3.14159265...

ρ_g - Gas density, kg/m^3.

ρ_l - Liquid density, kg/m^3.

ρ_p - Particle bulk density, kg/m^3.

σ - Attachment coefficient, dimensionless.

σ - Characteristic diameter of gaseous molecule, Å.

σ' - Coefficient for pollution obsorption with chemical reaction, equation 50, dimensionless.

σ_s - Surface tension, N/m.

τ - Dimensionless time, equation 22.

Φ_{ij} - Parameter defined by equation A.10.

ϕ - Fourier function, equation 58.

NOMENCLATURE (cont'd)

Greek Symbols (cont'd)

Ψ - Stream function, equation 1.

Ω_μ - Function of T/K obtained from viscosity data.

Ω_D - Function of T/K obtained from diffusivity data.

Superscripts

$'$ - Process in absence of chemical reactions.

$\sim$ - Molar property.

Subscripts

D - Droplet property or function of droplet diameter.

i,j. - Chemical species.

max - Maximum value.

P - Particle property or function of particle diameter

r - Relative value.

1,2 - Denotes either position or component.

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BIBLIOGRAPHY

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APPENDIX A

PHYSICAL AND THERMODYNAMICAL PROPERTIES

APPENDIX A

PHYSICAL AND THERMODYNAMICAL PROPERTIES

The various physical, chemical and thermodynamical properties of the chemical species involved in the molten salt scrubbing process are compiled in this appendix.

The density of the molten alkali-carbonate eutectic consisting of Na_2CO_3-Li_2CO_3-K_2CO_3 (43.5-31.5-25.0 mol%) is given by

$$\rho_l = 2512.8 - 0.5441 \times T \qquad \text{(A.1)}$$

The density of the gaseous mixture can be obtained by using ideal gas law,

$$P = \rho_g RT \qquad \text{(A.2)}$$

The specific heat of the ternary eutectic is given by

$$C_p\ (s) = 29.1 + 0.2068\ T \qquad \text{(A.3)}$$

which is valid for temperatures between 540°K to 670°K.

The specific heat of the liquid phase is given by,

$$C_p\ (\ell) = 119.0 + 69.4\ T \qquad \text{(A.4)}$$

which is valid for temperatures between 670°K and 1100°K.
The units of Cp are kJ/kgmol-°K.

The viscosity of the molten carbonate mixture is given by (20),

$$\mu(\ell) = 27.943118 + 0.02967\ T \qquad \text{(A.5)}$$

The surface tension of the liquid phase is given by,

$$\sigma_s = 0.2871 - 6.94 \times 10^{-5} \times T \qquad \ldots(A.6)$$

The Henry's law constant for H_2S solubility in fused carbonates is approximated by,

$$H = 2.854 \times 10^{6} \quad \rho_l \quad \exp\,(21.05 \times 10^{6}/RT)/M_w \qquad \ldots(A.7)$$

The diffusivity of gases in the liquid phase is given by Wilke and Chang equation (29)

$$D_i = 7.4 \times 10^{-15} \quad \frac{\psi_i M_w^{0.5} T}{\mu_l \tilde{V}_g^{0.6}} \qquad \ldots(A.8)$$

In this equation, ψ_i, is the association parameter. In this study, it has been assumed to be unity.

The viscosity of the gaseous mixture is obtained by,

$$\mu_{mix} = \sum_{i=1}^{n} \frac{X_i \mu_i^{\circ}}{\sum_{j=1}^{n} X_j \Phi_{ij}} \qquad \ldots(A.9)$$

in which,

$$\Phi_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_i^{\circ}}{M_j^{\circ}}\right)^{-0.5} \left(1 + \left(\frac{\mu_i^{\circ}}{\mu_j^{\circ}}\right)^{0.5} \left(\frac{M_j^{\circ}}{M_i^{\circ}}\right)^{0.25}\right)^2 \qquad \ldots(A.10)$$

$$\Phi_{ij} = 1 \qquad \text{when } i=j$$

The viscosity of individual gaseous species is obtained from,

$$\mu_i = 2.6693 \times 10^{-6} \frac{(M_i T)^{0.5}}{\sigma^2 \Omega_\mu} \quad \ldots (A.12)$$

Here,

$$\sigma = 0.841 \, (V_c)^{0.33} \quad \ldots (A.13)$$

$$\Omega_\mu = f \, (T/K) \quad \ldots (A.14)$$

The values of Ω may be obtained from Reid et al (28), or by using Lennard-Jones potential function.

The diffusivity of a gaseous species in a multicomponent mixture may be defined as,

$$D_{im} = \frac{1 - x_i}{\sum_{j=1}^{n} x_j / \mathcal{D}_{ij}} \quad \text{when } j \neq i \quad \ldots (A.16)$$

Here, the binary diffusivity is obtained from Chapman-Enskoy theory (29),

$$\mathcal{D}_{ij} = 18.8302 \times 10^{-3} \frac{T^{1.5} \left(\frac{1}{M_i} + \frac{1}{M_j} \right)^{0.5}}{P \sigma^2 \Omega_D} \quad \ldots (A.17)$$

Tables A-1 to A-3 list some thermochemical properties of the various species involved in the scrubbing process. Figures A.1 and A.2 show the phase diagrams for ternary systems.

TABLE A-1

THERMOCHEMICAL DATA FOR THE SPECIES INVOLVED IN THE MOLTEN SALT SCRUBBING PROCESS

Symbols: ΔH_f^o = standard isothermal enthalpy change for the formation reaction from the most stable phases of the elements at 298.16 K and 100.00 KPa, kJ/kgmol

S^o = absolute of Third Law entropy of the phase at 298.16 K and 100.00 KPa, kJ/kgmol ^oK

$Cp = A + BT + C/T^2 + DT^2$
Cp in kJ/kgmol ^oK and T in ^oK

A, B, C, D = constants for heat capacity equation

FORMULA	NAME	PHASE AND (ΔH_t)	$\Delta H_f^o \times 10^{-3}$	S^o	RANGE, K	A	B $\times 10^3$	C $\times 10^{-5}$	D $\times 10^6$
C	carbon	graphite	0.0	5.732	298 - 1100	0.109	38.903	- 1.480	- 17.368
			1.887	10.795	1100 - 4073	24.415	0.435	- 31.597	0.0
Ca	calcium	solid-A (0.22)*	0.0	41.420	298 - 720	24.102	- 3.352	0.333	20.394
		solid-B (2.04)	4.058	50.000	720 - 1112	- 0.376	41.240	0.0	0.0
		liquid (36.72)	12.175	52.216	1112 - 1757	29.260	0.0	0.0	0.0
CaS	calcium sulfide	oldamite	- 476.14	56.484	298 - 2000	45.140	7.733	0.0	0.0
CH_4	methane	gas	- 74.81	186.188	298 - 2000	12.436	76.615	1.446	- 17.987

* ΔH_t values shown in brackets, where H_t is the heat of transition in kJ/kgmol or standard enthalpy change for the transformation of Ca (solid-A) to Ca (solid-B) at 720° K.

TABLE A-1 (cont'd)

THERMOCHEMICAL DATA FOR THE SPECIES INVOLVED IN THE MOLTEN SALT SCRUBBING PROCESS (cont'd)

FORMULA	NAME	PHASE AND (ΔH_t)	$\Delta H_f^\circ \times 10^{-3}$	S°	RANGE, K	A	B $\times 10^3$	C $\times 10^{-5}$	D $\times 10^6$
CO	carbon monoxide	gas	- 110.54	197.552	298 - 2500	28.41	4.100	- 0.46	0.0
CO_2	carbon dioxide	gas	- 393.51	213.635	298 - 2500	44.14	9.037	- 8.535	0.0
COS	carbon oxide sulfide	gas	- 141.84	231.375	298 - 1800	47.40	9.121	- 7.657	0.0
CS_2	carbon disulfide	liquid (6.5)	89.41	151.335	298 - 319	76.99	0.0	0.0	0.0
		gas	117.24	238.697	298 - 2000	49.57	13.276	- 7.012	- 3.653
$FeCO_3$	iron carbonate	siderite	- 740.568	92.885	298 - 800	48.660	112.098	0.0	0.0
FeS	iron monosulfide	solid-A(0.570)	- 100.416	60.291	298 - 411	0.502	167.36	0.0	0.0
		solid-B(0.120)	- 99.495	61.756	411 - 598	72.801	0.0	0.0	0.0
		solid-C(7.73)	- 93.805	74.768	598 - 1468	51.045	9.958	0.0	0.0
		liquid	- 74.68	76.44	1468 - 2000	71.128	0.0	0.0	0.0
FeS_2	iron disulfide	solid	- 171.544	52.95	298 - 1016	74.764	5.577	-12.740	0.0
H_2	hydrogen	gas		130.582	298 - 3000	27.280	3.284	0.502	0.0
H_2O	water	liquid (9.82)	- 285.85	69.96	298 - 373	75.438	0.0	0.0	0.0
	steam	gas	- 241.626	189.368	373 - 2500	30.000	10.711	0.335	0.0
H_2S	hydrogen sulfide	gas	- 20.502	205.685	298 - 1800	29.372	15.397	0.0	0.0

TABLE A-1 (cont'd)

THERMOCHEMICAL DATA FOR THE SPECIES INVOLVED IN THE MOLTEN SALT SCRUBBING PROCESS (cont'd)

FORMULA	NAME	PHASE AND (ΔH_t)	$H_f^\circ \times 10^{-3}$	S°	RANGE, K.	A	B $\times 10^{3}$	C $\times 10^{-5}$	D $\times 10^{6}$
K	potassium	solid		64.685	298 - 336	7.837	71.915	0.0	0.0
		liquid	2.259	71.421	336 - 1037	37.179	- 19.12	0.0	12.318
K_2CO_3	potassium carbonate	solid (6.60)	- 1150.182	155.519	288 - 1174	97.926	92.08	- 9.907	0.0
		liquid	- 1162.734	101.964	1174 - 2000	209.2	0.0	0.0	0.0
K_2S	potassium sulfide	solid-A(0.010)	- 414.216	112.968	298 - 1100	70.208	19.832	0.0	0.0
		solid-B(3.860)	- 460.909	34.727	1100 - 1221	142.340	0.0	0.0	0.0
		liquid	- 406.559	97.906	1221 - 1500	100.960	0.0	0.0	0.0
Li	lithium	solid	0.0	29.08	298 - 454	13.941	34.359	0.0	0.0
		liquid	2.092	33.10	454 - 1200	24.476	5.473	8.648	- 1.954
Li_2CO_3	lithium carbonate	solid-A(0.134)	- 1215.87	90.17	298 - 623	42.530	177.339	0.0	0.0
		solid-B(0.535)	- 1206.67	110.71	623 - 683	14.364	180.749	0.0	0.0
		solid-C(10.70)	- 1204.16	113.97	683 - 993	14.364	180.749	0.0	0.0
		liquid	- 1197.46	78.87	993 - 2000	185.435	0.0	0.0	0.0
Li_2S	lithium sulfide	solid	- 446.4	60.67	298 - 1223	66.316	201.167	0.0	0.0
Na	sodium	solid (0.62)	0.0	51.17	298 - 371	14.790	44.229	0.0	0.0
		liquid	2.402	57.57	371 - 1156	37.468	- 19.154	0.0	10.627
Na_2S	sodium sulfide	solid (6.30)	- 374.47	79.50	298 - 1251	82.885	6.862	0.0	0.0
		liquid	- 351.46	94.14	1251 - 2200	92.048	0.0	0.0	0.0
Na_2CO_3	sodium carbonate	solid-A(0.165)	- 1130.77	138.78	298 - 723	11.016	244.036	24.493	0.0
		solid-B(7.09)	- 1116.92	165.39	723 - 1123	50.08	129.076	0.0	0.0
		liquid	- 1126.63	113.34	1123 - 2000	189.535	0.0	0.0	0.0
SO_2	sulfur dioxide	gas	- 296.81	248.11	298 - 1800	43.430	10.627	5.941	0.0

TABLE A-2

EUTECTIC COMPOSITION, MELTING POINTS AND HEAT OF FUSION OF SOME MOLTEN SALT MIXTURES (20)

MOLTEN SALTS	COMPOSITION (mole %)	TEMPERATURE (^{o}K)	HEAT OF FUSION kJ/kgmol)
Na_2CO_3 - K_2CO_3	56, 44	983	19664.8
K_2CO_3 - Li_2CO_3	57, 43	771	36400.8
Na_2CO_3 - Li_2CO_3	50, 50	778	35982.4
Na_2CO_3 - K_2CO_3 - Li_2CO_3	31, 25, 44	670	27614.4

TABLE A.3

HEAT OF COMBUSTION OF SOME PRODUCT GASES

AT 298.15° K and 0.1 MPa

Gases	Heat of Combustion* MJ/kgmol
CO	282.964
H_2	285.855
CH_4	890.410
C_2H_6	1559.896

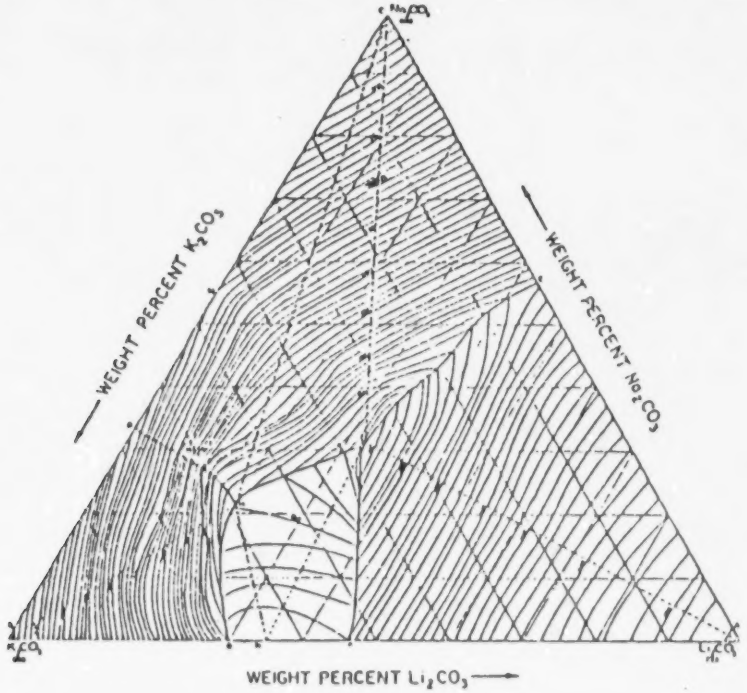


Figure A.1 Phase Diagram for Na_2-K_2-Li_2CO_3 Ternary System (29). All Temperatures are in Degrees Celsius.

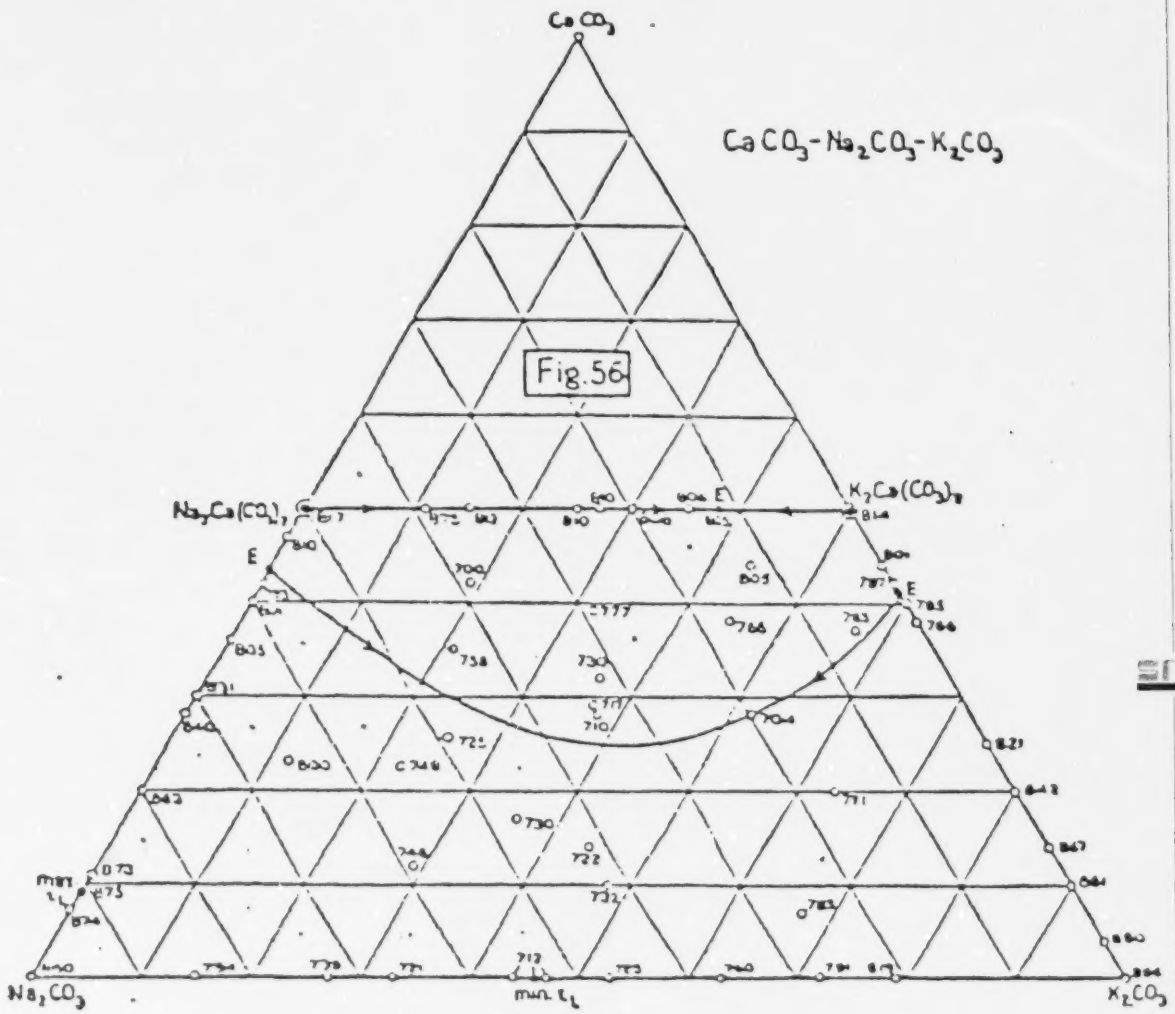


Figure A.2 Phase Diagram for Na_2CO_3-K_2CO_3-$CaCO_3$ Ternary System. All Temperatures are in Degrees Celsius.

APPENDIX B

EQUILIBRIUM DATA

APPENDIX B

EQUILIBRIUM DATA

The following are the main chemical reactions taking place between the molten carbonates and hydrogen sulfide:

$$Li_2CO_3 + H_2S \rightleftharpoons Li_2 + CO_2 + H_2O \quad ...(B.1)$$
$$K_2CO_3 + H_2S \rightleftharpoons K_2S + CO_2 + H_2O \quad ...(B.2)$$
$$CaCO_3 + H_2S \rightleftharpoons CaS + CO_2 + H_2O \quad ...(B.3)$$
$$FeCO_3 + H_2S \rightleftharpoons FeS + CO_2 + H_2O \quad ...(B.4)$$
$$Na_2CO_3 + H_2S \rightleftharpoons Na_2S + CO_2 + H_2O \quad ...(B.5)$$

Apart from these, each of the above carbonate salts react with CO:

$$M_xCO_3 + CO \rightleftharpoons xM + 2\ CO_2 \quad ...(B.6)$$

Table B-1 gives equilibrium constants for reactions (B.1) through (B.5) at different temperatures.

TABLE B-1

EQUILIBRIUM CONSTANTS FOR THE REACTION OF CARBONATES WITH HYDROGEN SULFIDE

$$M_xCO_3 + H_2S = CO_2 + H_2O + M_xS$$

where M = Na, Li, K, Ca, etc., and x = 1 or 2

RXN. NO	M_xCO_3	EQUILIBRIUM CONSTANTS AT			
		973°K	1073°K	1173°K	1273°K
B.1	Li_2CO_3	2.10	6.09	14 05	27.4
B.2	K_2CO_3	17 05	51.64	122.21	241.1
B.3	$CaCO_3$	109 9	347.2	897 8	1.98
B.4	$FeCO_3$	$3\ 26\times10^{7}$	3.98×10^{7}	4.67×10^{7}	4.81×10^{7}
B.5	Na_2CO_3	0.193	0 791	2.43	6.0

* Equilibrium constants have been calculated from Gibbs Free Energy Data (G), Table A-1.

TABLE B-2

THERMODYNAMIC PROPERTIES FOR SCRUBBING REACTIONS WITH Na_2CO_3

REACTIONS	T	ΔH	ΔG	ΔS	ΔU
$Na_2CO_3 + CO \rightleftharpoons 2Na + 2CO_2$	973	145398	70886	76.6	139598
	1073	143596	63318	74.8	137200
	1173	141835	55916	73.2	134842
	1273	140111	48663	71.8	132523
$Na_2CO_3 + H_2O \rightleftharpoons 2NaOH + CO_2$	973	30883	19304	11.9	30883
	1073	30630	18127	11.6	30630
	1173	30376	16973	11.4	30376
	1273	29862	15841	11.2	30121
$Na_2S + 2CO_2 \rightleftharpoons Na_2CO_3 + COS$	973	- 22256	3520	- 26.5	- 20322
	1073	- 21100	6111	- 25.4	- 18968
	1173	- 19970	8596	- 24.3	- 17639
	1273	- 18863	10986	- 23.4	- 16334
$Na_2CO_3 + H_2S \rightleftharpoons Na_2S + CO_2 + H_2O$	973	29774	3176	27.3	27840
	1073	28601	501	26.2	26469
	1173	27442	- 2066	25.1	25111
	1273	26297	- 4534	24.2	23766

APPENDIX C

DESIGN CRITERIA

APPENDIX C

DESIGN CRITERIA (32)

Inlet gas temperature, ^{o}C	450^{o} - $1000^{o}C$
Gas Composition	(see Appendix D)
Pressure, MPa	<3.0
Gas flowrate, Nm^3/s	10 - 40
Particulate collection efficiency,%	99.99
H_2S removal efficiency,%	>95.0
KCl/NaCl content of exit stream, ppmv	$<.4$
Cut diameter of particulates	0.5 μm
Particulate loading, gm/m^3	<2.3
Particulate density, kg/m^3	1200 - 2000
Scrubbing liquid	Na_2CO_3-K_2CO_3-Li_2CO_3 with $FeCO_3$ and/or $CaCO_3$
Maximum pressure drop, MPa	0.025
Outlet sulfur content, ppm	0.5

APPENDIX D

COMPOSITION OF FUEL GAS FROM IGT U-GAS GASIFIER

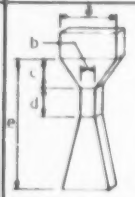
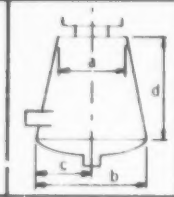
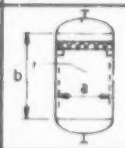
APPENDIX D

COMPOSITION OF FUEL GAS FROM IGT U-GAS CASIFIER (32)

Component	Volume %	Weight %
N_2	51.2	57.8
CO	21.5	24.3
CO_2	8.2	14.5
H_2	16.7	1.4
CH_4	1.6	1.0
NH_3 (ppm)	320	--
H_2S (ppm)	7,220	1.0
COS (ppm)	212	--
HCl (ppm)	110	--
KCl (ppm)	2.1	--
NaCl (ppm)	0.8	--
Tar	nil	
Paticulates, g/Nm^3	73.8	
Temperature, ^oC	1,000	--
Pressure, MPa	0.1	

APPENDIX E

SPECIFICATIONS AND DATA FOR EQUIPMENT

NAME	SKETCH	DIMENSION (m)	GAS TO	QUANTITY 20	(Nm^3/s) AO	MATERIAL OF CONSTRUCTION
VENTURI		a b c d e	2.6/0.8 0.5 1.8 0.75 10.6	3.5/1.2 0.7 2.6 1.0 15.0	5.0/1.7 1.0 3.2 3.0 22.5	In-671 or In-800 Aluminum red lined with fused Al_2O_3 such as Monotrex A
CONICAL SEPARATOR		a b c d	3.2 5.2 8.5 6.5	4.7 7.6 12.4 9.5	6.8 10.8 17.5 14.0	as above
K.O. DRUM		a b	2.5 7.0	3.6 9.0	5.0 12.0	as above
MAKE-UP TANK		V (m^3) M (kW)	1.0 600	1.5 900	2.5 1 500	as above
ACID EGG PUMP		V (m^3)	1.1	2.2	2.5	as above
MOLTEN SALT FURNACE		V (m^3) M (kW)	2.0 100	3.5 200	7.0 380	as above
SHELL & TUBE HEAT EXCHANGER TYPE TEMA AEP		20' Long 4' Dia. TUBE SIZE 3/4" No OF HE 4 AREA OF EACH 5675 ft^2				as above

SNC Surveyer, Nenniger & Chênevert Inc.
1, Complexe Desjardins, Montréal, Canada

BRIEF SPECIFICATION OF
HOT SCRUBBING EQUIPMENT

APPENDIX F

COST ESTIMATE

3303 Rev. 6-82

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project: Coal Gasification

Lieu/Location

Sub-Sub Unit / Area Unit: HOT GAS CLEAN-UP SYSTEM

Metric Take-off: ltspencer

Evalue Price: —ditto—

Verifie par / Checked by

Date: 88.10.01

Page/Sheet: 1 De/Of: 8

Contr: 6615 Subd: Sujet/Subject:

Code Coût / Cost Code	Description	Quan	U	Heures hommes / Manhours U	Total	Coût / Cost	Coût unitaire / Unit Cost Mat'l	L.S.	S.C.	Main d'oeuvre / Labour	Mat. Equip	Sous-contrat / Sub-contract	Total
	ORDER OF MAGNITUDE												
	Principle Equipment Cost based on Carbon Steel												
1	Plant Equipment	50%											6331000
2	Electrical & Instrumentation	6%											759000
3	Piping	7%											886000
4	Civil & Structural	18%											2279000
5	Insulation & Painting etc	4%											506000
6	Installation & Construction	15%											1899000
7	Direct Plant Cost -	100%	- Based on Carbon Steel										12660000
8	Indirect Costs (6) x	120%											2278000
9.	S/T												14938000
10	Engineering & Construction Management: 25% of (9)												3734000
11.	S/T												18672000
12	Contingency (11) x	20% ±											3734000
13.	TOTAL SYSTEM COST - Based on Carbon Steel												22406000
14	SS 304L Materials Adjustment for VESSELS & DUCTS												488000
15.	" " " PIPING & VALVES												246000
16.	TOTAL SYSTEM COST - Using Exotic Materials												23140000

3303 Rev 6/82

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project: Coal Gasification

Lieu/Location

Area / Unit: HOT GAS CLEAN-UP SYSTEM

Made by / Fait par: RSpencer

Verified by / Vérifié par

Date: 82.10.01

Page Sheet: 2 De Of: 8

Contr: 6615 Subd: Suject Subject:

Code Coût Cost Code	Description	Quan	U	Heures-hommes Manhours U	Heures-hommes Manhours Total	Coût Cost	Coût unitaire Unit Cost Matl	Main d'oeuvre Labour	Mat. Equip.	Sous contrat Sub contract	Total
	ORDER OF MAGNITUDE										
	SUMMARY OF PRINCIPAL EQUIPMENT										
	VENTURI							176000	327000		503000
	HEAT EXCHANGER							1652000	1516000		3168000
	CONICAL SEPARATOR							210000	830000		1040000
	K.O. DRUM							126000	287000		413000
	MAKE-UP TANK							63000	92000		163000
	EGG PUMPS							207000	255000		462000
	MOLTEN SALT FURNACE							28000	252000		280000
	TRANSFORMERS & SWITCHGEAR							10000	80000		90000
	VENTURI TO CONICAL SEPARATOR (DUCT)							23000	75000		98000
	CONICAL SEPARATOR TO KO DRUM (DUCT)							60000	395000		455000
	6% Materials Waste Adjustment (Carbon Steel)								16000		16000
	6% " " " (Incolloy)								21000		21000
	Freight & Handling Allowance							110000			110000
	PRINCIPAL EQUIPMENT COST - F.O.B. SITE							2673000	4146000		6819000
	SS304L Material Cost Adjustment included into above total								<488000>		<488000>
	PRINCIPAL EQUIPMENT COST - FOB SITE (based on Carbon Steel)							2673000	3658000		6331000

3303 Rev 6/82

SNC

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification.

Lieu/Location

Section/Unité/Area/Unit HOT GAS CLEAN UP SYSTEM

Métré par/Take off A.Spencer

Évalué par/Priced --d:tto--

Vérifié par/Checked by

Date 82.10.01

Page/Sheet 3 De/Of 8

Code 6615 | Subd | Sujet/Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Total	Coût / Cost	Coût unitaire / Unit Cost Matl	Main d'oeuvre / Labour	Mat. Équip.	Sous-contrat / Sub-contract	Total
	VESSELS										
	All vessels are priced using Carbon Steel ASTM A516 grade 70 as the base material. An exotic materials adjustment will be made separately.										
	VENTURI										
	Fab shop time	1000	hrs		1000	7500		75000			
	Base Material	15300	lbs				0.45		7000		
	SS304L Material Adjustment	15300	lbs				1.05		16000		
	Stellite 6B-Surfacing	270	SF	5.0	1350	75.00		101000			
	of Venturi Throat	6750	lbs (Weld Rod)			45.00			304000		
	Using 1/4 Rod S/T							176000	327000		503000
	Field Erection	1	Lot		1200	40.00		48000			48000
	VENTURI TOTAL							224000	327000		551000

3303 Rev. 6/82

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project

Lieu/Location Coal Gasification

Secteur/Unité / Area/Unit HOT GAS CLEAN-UP SYSTEM

Mètre/Take off ft Spencer

Évalué/Priced —ditto

Vérifié par/Checked by

Date

Page/Sheet 4 De/Of 8

Contr 6615 | Subd | Sujet/Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Heures-hommes / Manhours Total	Coût / Cost	Coût unitaire / Unit Cost Mat'l	Coût unitaire / Unit Cost c/s/s/c	Main d'oeuvre / Labour	Mat./Equip	Sous-contrat / Sub-contract	Total
	Vessels (Cont'd)											
	HEAT EXCHANGER											
	Fabshop Time	5500	hrs			75.00			413000			
	Base Material	48000	lbs				0.45			21600		
	SS304L Material-Shell	48000	lbs				1.05			52800		
	Base Material-Bundle	5300	lbs				2.20			11700		
	Bundle Tubing - ___	45000	ft				6.50			292500		
	Cost per Unit								413000	379000		792000
	Cost for 4 Units								1652000	1516000		3168000
	Field Erection.				130				8000			8000
	TOTAL-HEAT EXCHANGERS								1660000	1516000		3176000

3303 Rev 6/82

ESTIMATION DES COÛTS / COST ESTIMATE

Client:
Projet/Project: Coal Gasification
Lieu/Location:
Secteur Unité / Area Unit: HOT GAS CLEAN UP SYSTEM
Metre Take-off: R Spencer
Evalue Priced: — ditto
Verifie par/Checked by:
Date: 82.10.01
Page/Sheet: 5 De/Of 8
Contr: G615
Subd:
Sujet / Subject:

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Man-hours U	Heures-hommes / Man-hours Total	Coût / Cost	Coût unitaire / Unit Cost Mat'l	Coût unitaire / Unit Cost C.S.T.	Main d'oeuvre / Labour	Mat./Equip	Sous-contrat / Sub-contract	Total
	VESSELS (Cont'd)											
	CONICAL SEPARATOR											
	Fabshop time	2800				75.00			210000			
	Base Material	128000	lbs				0.45			58000		
	SS 304L Material Adjustment	128000	lbs				1.05			134000		
	Refractory Lining & Bake-off	7972	SF			80.00				638000		
	S/T								210000	830000		1040000
	Field Erection	1	lot		1500	40.00			60000			60000
	CONICAL SEPARATOR TOTAL								270000	830000		1100000
	K.O. DRUM.											
	Fabshop time ①	1200				75.00			90000			
	Base Material ②	43200	lbs				0.45			19000		
	Internals 40% of ① & ②								36000	8000		
	S.S. 30L Materials Adjustment	43200	lbs				1.05			45000		
	Refractory Lining & Bake-off	2690	SF			80.00				215000		
	S/T								126000	287000		413000
	Field Erection	1	lot		300	40.00			12000			12000
	KO DRUM TOTAL								138000	287000		425000

SNC **ESTIMATION DES COÛTS COST ESTIMATE**

Client

Projet/Project Coal Gasification

Lieu/Location

Secteur/Unité Area Unit HOT GAS CLEAN-UP SYSTEM

Metre Take-off R Spencer

Évalué Priced —ditto—

Vérifié par/Checked by

Date 82.10.01

Page/Sheet 6 De/Of 8

Contr 6615 | Subd | Sujet Subject

Code Coût Cost Code	Description	Quan	U	Heures-hommes Manhours U	Total	Coût Cost	Coût unitaire Unit Cost Mat'l	c/s/ s/c	Main-d'oeuvre Labour	Mat /Equip	Sous-contrat Sub-contract	Total
	VESSELS (Cont'd)											
	MAKE-UP TANK											
	Fabshop time ①	600	hrs			75.00			45 000			
	Base Material ②	24000	lbs				0.85			16 000		
	Internals 40% of ① & ②								18 000	6 000		
	SS304L Materials Adjustment	24000	lbs				1.05			25 000		
	Refractory Lining & Bake-off	560	SF				80.00			45 000		
	S/T								63 000	92 000		155 000
	Field Erection			200		40.00			8 000			8 000
	MAKE-UP TANK TOTAL								71 000	92 000		163 000
	EGG PUMP - 3 Required											
	Fabshop time ①	2400	hrs			75.00			180 000			
	Base Material ②	70000	lbs				0.70			49 000		
	Internals 15% of ① & ②								27 000	7 000		
	Exotic Materials Adjustment	8700	lbs (Incolloy liner)				15.00			131 000		
	Refractory Lining & Bake-off	850	SF				80.00			68 000		
	S/T								207 000	255 000		462 000
	Field Erection			600		40.00			24 000			24 000
	EGG PUMPS TOTAL								231 000	255 000		486 000

3303 Rev. 6/82

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ESTIMATION DES COÛTS / COST ESTIMATE

Client:

Projet/Project: Coal Gasification

Lieu/Location:

Secteur/Unité / Area/Unit: HOT GAS CLEAN UP SYSTEM

Metre/Take-off: R Spencer

Évalué/Priced: -ditto-

Vérifié par/Checked by:

Date: 82.10.01

Page/Sheet: 7 De/Of 8

Contr.: 6615

Subd.:

Sujet/Subject:

Code Coût / Cost Code	Description	Quan	U	Heures-hommes Manhours U	Heures-hommes Manhours Total	Coût Cost	Coût unitaire Unit Cost Mat'l	Coût unitaire Unit Cost c/s/s/c	Main-d'oeuvre Labour	Mat/Equip	Sous-contrat Sub-contract	Total
	VESSELS											
	MOLTEN SALT FURNACE											
	Fabshop time ①	300	hrs			75 00			23000			
	Base Material ②	7000	lbs				0 57			4000		
	Internals Allow 20% of ①								5000	-		
	Exotic Materials Adjustment	7000	lbs	(Incolloy)			32 00			224000		
	Refractory Lining & Bake off	300	SF				80 00			24000		
	S/T								28000	252000		280000
	Field Erection	1	Lot		200	40 00			8000			8000
	MOLTEN SALT FURNACE TOTAL								36000	252000		288000
	TRANSFORMERS & SWITCHGEAR								10000	80000		90000

3303 Rev 6/82

(5)

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project: Coal Gasification

Lieu/Location

Secteur Unité / Area Unit: HOT GAS CLEAN-UP SYSTEM

Mettre Take-off: R Spencer

Évalué Priced: -ditto-

Verifié par/Checked by

Date: 82.10.01

Page/Sheet: 8 De/Of 8

Contr: 6615

Subd

Sujet / Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Heures-hommes / Manhours Total	Coût / Cost	Coût unitaire / Unit Cost Mat'l	c/s/s/c	Main d'oeuvre / Labour	Mat /Equip	Sous-contrat / Sub-contract	Total
	DUCTS											
	Venturi to Conical Separator											
	Fabshop time	300	hrs			75 00			23 000			
	Base Material	8700	lbs				0 45			4 000		
	SS304L Materials Adjustment	8700	lbs				1 05			9 000		
	Refractory Lining & Bake-off	780	SF				80 00			62 000		
	S/T								23 000	75 000		98 000
	Field Erection				100	40 00			4 000			4 000
	TOTAL								27 000	75 000		102 000
	Conical Separator to KO DRUM											
	Fab Shop time	800	hrs			75 00			60 000			
	Base Material	45700	lbs				0 45			21 000		
	SS304 L Materials Adjustment	45700	lbs				1 05			48 000		
	Refractory Lining & Bake-off	4070	SF				80 00			326 000		
	S/T								60 000	395 000		455 000
	Field Erection				400	40 00			16 000			16 000
	TOTAL								76 000	395 000		471 000

3308 Rev 6/82'

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Secteur Unité / Area Unit COLD GAS CLEAN-UP SYSTEM

Mètre/Take-off R Spencer

Évalué/Priced — ditto

Vérifié par/Checked by

Date

Page/Sheet 1 De/Of 10

Contr 6615 | Subd | Sujet/Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Heures-hommes / Manhours Total	Coût / Cost	Coût unitaire / Unit Cost Mat'l	Coût unitaire / Unit Cost c.s./s.c	Main-d'oeuvre / Labour	Mat./Equip	Sous-contrat / Sub-contract	Total
	ORDER OF MAGNITUDE											
	Principle Equipment Cost based on Carbon Steel											
1.	Plant Equipment	60	%									61 231 000
2.	Electrical & Instrumentation	2	%									2 041 000
3.	Piping	12	%									12 246 000
4.	Civil & Structural	5	%									5 102 000
5.	Insulation & Painting	6	%									6 123 000
6.	Installation & Construction	15	%									15 308 000
7.	S/T											102 051 000
8.	H_2S Absorber Tower											17 841 000
9.	Direct Plant Cost - Based on Carbon Steel											119 892 000
10.	Indirect Costs (9) × 120 %											18 370 000
11.	S/T											138 262 000
12.	Engineering & Construction Management: 20% of (11)											27 652 000
	S/T											165 914 000
13.	Contingency (12) × 20 %											33 183 000
14	TOTAL SYSTEM COST - Based on Carbon Steel											199 097 000
15	SS304L Material Adjustment for VESSELS & DUCTS											9 354 000
16	" " " " PIPING & VALVES											1 931 000
	TOTAL SYSTEM COST - Using S.S 304L											210 382 000

3303 Rev 6/82

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Secteur Unité Area Unit COLD GAS CLEAN-UP SYSTEM

Metre Take-off R.T. Spencer

Évalue Priced — ditto —

Verifié par/Checked by

Date

Page/Sheet 2 De/Of 10

Contr 6615 | Subd | Sujet Subject

Code Coût Cost Code	Description	Quan	U	Heures-hommes Manhours U	Heures-hommes Manhours Total	Coût Cost	Coût unitaire Unit Cost Mat'l	C/S/S C	Main d'oeuvre Labour	Mat /Equip	Sous-contrat Sub-contract	Total
	ORDER OF MAGNITUDE											
	SUMMARY OF PRINCIPLE EQUIPMENT											
	VENTURI								154000	346000		500000
	CONICAL SEPARATOR								187500	98500		286000
	VENTURI to CONICAL SEPARATOR (DUCT)								23000	13000		36000
	CONICAL SEPARATOR to DEMISTER (DUCT)								60000	66000		126000
	K.O. DRUM								126000	88000		214000
	DEMISTER								126000	88000		214000
	HEAT EXCHANGERS								8260000	5344000		13604000
	STEAM GENERATORS								12390000	8016000		20406000
	GAS COOLERS								19824000	12826000		32650000
	PUMPS									93000		93000
	6% Materials Waste Adjustment									175000		175000
	Freight & Handling Allowance								40000	60000		100000
	PRINCIPAL EQUIPMENT COST - F.O.B. SITE (Excluding H_2S Absorber Tower)								41190500	27125500		68316000
	Material Cost Difference 64412 lbs C.S. ASTM A517 Gr 70 to SS304L						1.10			<7085000>		<7085000>
	PRINCIPAL EQUIPMENT COST - F.O.B SITE (based on Carbon Steel)								41190500	20040500		61231000

3308 Rev 6/82

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Area Unit COLD GAS CLEAN-UP SYSTEM

Metric Take-off RSpencer

Estimé par/Checked by

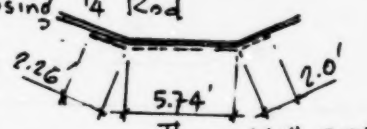
Date

Estimé par/Estimated by — ditto —

Page/Sheet 3 De/Of 10

Contr 6615 | Subd | Sujet/Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Total	Coût / Cost	Coût unitaire / Unit Cost Matl	C.S./S.C.	Main d'oeuvre / Labour	Mat./Equip	Sous-contrat / Sub-contract	Total
	VESSELS											
	VENTURI											
	Approximately 2/3 of Hot Gas Venturi weight.											
	Fabshop time	700	hrs		700	75.00			53 000			
	Base Material - S.S. 304 L	29000	lbs				1.45			42 000		
	Using 3/8 Plate skin											
	Frame & Fittings - Carbon Steel	5000	lbs				0.45			2200		
	Stellite 6B - Surfacing of Venturi throat	270	SF	5.0	1350	75.00			101 000			
	using 1/4 Rod	6750	lbs				45.00			303 800		



Throat Width 9.84'
Throat Depth 3.28'

	S/T								154 000	346 000		500 000
	Field Erection	1	Lot	1000		40.00			40 000			40 000
	VENTURI TOTAL								194 000	346 000		540 000

3303 Rev 6/82

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Area Unit COLD GAS CLEAN-UP SYSTEM

Verifie par Checked by

Date

Page Sheet 4 De/Of 10

Contr 6615 | Subd | Sujet Subject

Code Coût Cost Code	Description	Quan	U	Heures-hommes Manhours U	Total	Cout Cost	Cout unitaire Unit Cost Mat'l		Main d'oeuvre Labour	Mat'l/Equip	Sous-contrat Sub-contract	Total
	VESSELS (Cont'd)											
	CONICAL SEPARATOR											
	Approximately 55% of Hot Gas con/sep weight											
	Fabshop time	2500	hrs			75.00			187500			
	Base Material - SS 304 L	67000	lbs.				1.45			97000		
	Using 3/8 Plt skin											
	Frame & Fittings - Carbon Steel	3300	lbs.				0.45			1500		
	S/T								187500	98500		286000
	Field Erection	1	Lot		1200	40.00			48000			48000
	CONICAL SEPARATOR - TOTAL								235500	98500		334000

3303 Rev 6/82

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Secteur Unité / Area Unit COLD GAS CLEAN-UP SYSTEM

Mettre/Take off H. Spencer

Évalué/Priced —ditto—

Vérifié par/Checked by

Date

Page/Sheet 5 De/Of 10

Contr 6615 Subd Sujet/Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes Manhours U	Total	Coût / Cost	Coût unitaire Unit Cost Mat'l	C.S./S.C.	Main d'oeuvre / Labour	Mat./Equip	Sous-contrat / Sub-contract	Total
	VESSELS (DUCTS)											
	Venturi to Conical Separator											
	Use same weight as for the HOT GAS SYSTEM											
	Fab shop time	300	hrs			75.00			23000			
	Base Material - SS 304 L	8700	lbs				1.45			13000		
	S/T								23000	13000		36000
	Field Erection				100	40.00			4000			4000
	TOTAL								27000	13000		40000
	Conical Separator to Demister (same weight as HOT GAS SYSTEM)											
	Fab shop time	800	hrs			75.00			60000			
	Base Mat'l - SS 304 L	45700	lbs				1.45			66000		
	S/T								60000	66000		126000
	Field Erection				400	40.00			16000			16000
	TOTAL								76000	66000		142000

3308 Rev 6/82

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Secteur Unité
Area Unit COLD GAS CLEAN-UP SYSTEM

Métré Take off R.Spencer

Evalué Priced —ditto—

Vérifié par/Checked by

Date

Page/Sheet 6 De/Of 10

Contr 8615 | Subd | Sujet Subject

Code Coût Cost Code	Description	Quan	U	Heures-hommes Manhours U	Total	Coût Cost	Coût unitaire Unit Cost Mat'l	c/S s/c	Main d'oeuvre Labour	Mat./Equip	Sous-contrat Sub-contract	Total
	VESSELS (Cont'd)											
	K.O. DRUM.											
	Use same weight as for Hot Gas System.											
	Fabshop time ①	1200	hrs			75 00			90000			
	Base Material - SS 304 L ②	43200	lbs				1 45			63000		
	Internals 40% of ① & ②								36000	25000		
	S/T								126000	88000		214000
	Field Erection	1	Lot	300		40 00			12000			12000
	K.O. DRUM TOTAL								138000	88000		226000
	DEMISTER											
	Use same figure as for K.O. Drum.											226000

3308 Rev 6/82

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Section/Unité Area/Unit COLD GAS CLEAN-UP SYSTEM

Métré/Take-off ltspencer

Évalué/Priced —ditto—

Vérifié par/Checked by

Date

Page/Sheet 7 De/Of 10

Contr 6615 | Subd | Sujet/Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Heures-hommes / Manhours Total	Cout / Cost	Cout unitaire / Unit Cost Mat'l	c/s/s.c	Main d'oeuvre / Labour	Mat./Equip	Sous-contrat / Sub-contract	Total
	VESSELS (Cont'd)											
	HEAT EXCHANGER											
	Fabshop time	5500	hrs			75.00			413000			
	Base Material - Shell	58000	lbs				1.55			89900		
	Base Material - Bundle	5300	lbs				2.20			11700		
	Bundle Tubing	24000	ft				6.90			165600		
	Cost per unit								413000	267200		642200
	Cost for 20 units.								8260000	5344000		13604000
	Field Erection			650		40.00			26000			26000
	TOTAL - HEAT EXCHANGERS								8286000	5344000		13630000

3303 Rev 6/82

ESTIMATION DES COÛTS / COST ESTIMATE

Client

Projet/Project: Coal Gasification

Lieu/Location

Sujet/Subject: COLD GAS CLEAN-UP SYSTEM

Métré par/Taken off by

Vérifié par/Checked by

Evalué par/Priced

Date

Page/Sheet: 8 De/Of 10

Contr: 6615 Subd: Sujet/Subject:

Code Cout / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Heures-hommes / Manhours Total	Cout / Cost	Cout unitaire / Unit Cost Mat'l	Cout unitaire / Unit Cost	Main d'oeuvre / Labour	Mat'l / Equip	Sous-contrat / Sub-contract	Total
	VESSELS (Cont'd)											
	STEAM GENERATORS											
	Use same unit costs as developed for Hxchgrs. 27 online 3 standby	30				413k	267.2k		12390000	8016000		20406000
	Field Erection	30				1.3k			39000			39000
	TOTAL - STEAM GENERATORS								12429000	8016000		20445000
	GAS COOLERS											
	Use same unit costs as developed for Hxchgrs. 45 online 3 Standby	48				413k	267.2k		19824000	12826000		32650000
	Field Erection	48				1.3k			62000			62000
	TOTAL - GAS COOLERS								19886000	12826000		32712000

3302 Rev 6/82

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project: Coal Gasification

Lieu/Location

Secteur Unité / Area Unit: COLD GAS CLEAN-UP SYSTEM

Mètre Take-off: H Spencer

Évalué Priced: —ditto—

Vérifié par / Checked by

Date

Page/Sheet: 9 De/Of 10

Contr: 6615 Subd: Sujet Subject:

Code Coût Cost Code	Description	Quan	U	Heures-hommes Manhours U	Heures-hommes Manhours Total	Coût Cost	Coût unitaire Unit Cost Mat'l	Coût unitaire Unit Cost c s/ s c	Main-d'oeuvre Labour	Mat / Equip	Sous-contrat Sub-contract	Total
	PUMPS											
	Flow rate 1240 us gpm Select 2-750 us g'm electrics 170 psi, 100 HP 3500 RPM 5" Pump	2					16k			32000		
	Select 1-1500 us gpm diesel standby 200 psi 285 HP 6" pump	1								61000		
	S/T									93000		93000
	Field Erection				100	40.00			4000			4000
	TOTAL - PUMPS								4000	93000		97000

3303 Rev 6/82

ESTIMATION DES COÛTS COST ESTIMATE

Client

Projet/Project Coal Gasification

Lieu/Location

Secteur Unité / Area Unit COLD GAS CLEAN-UP SYSTEM

Mesure / Take-off R.Spencer

Évalué / Priced — ditto —

Vérifié par / Checked by

Date

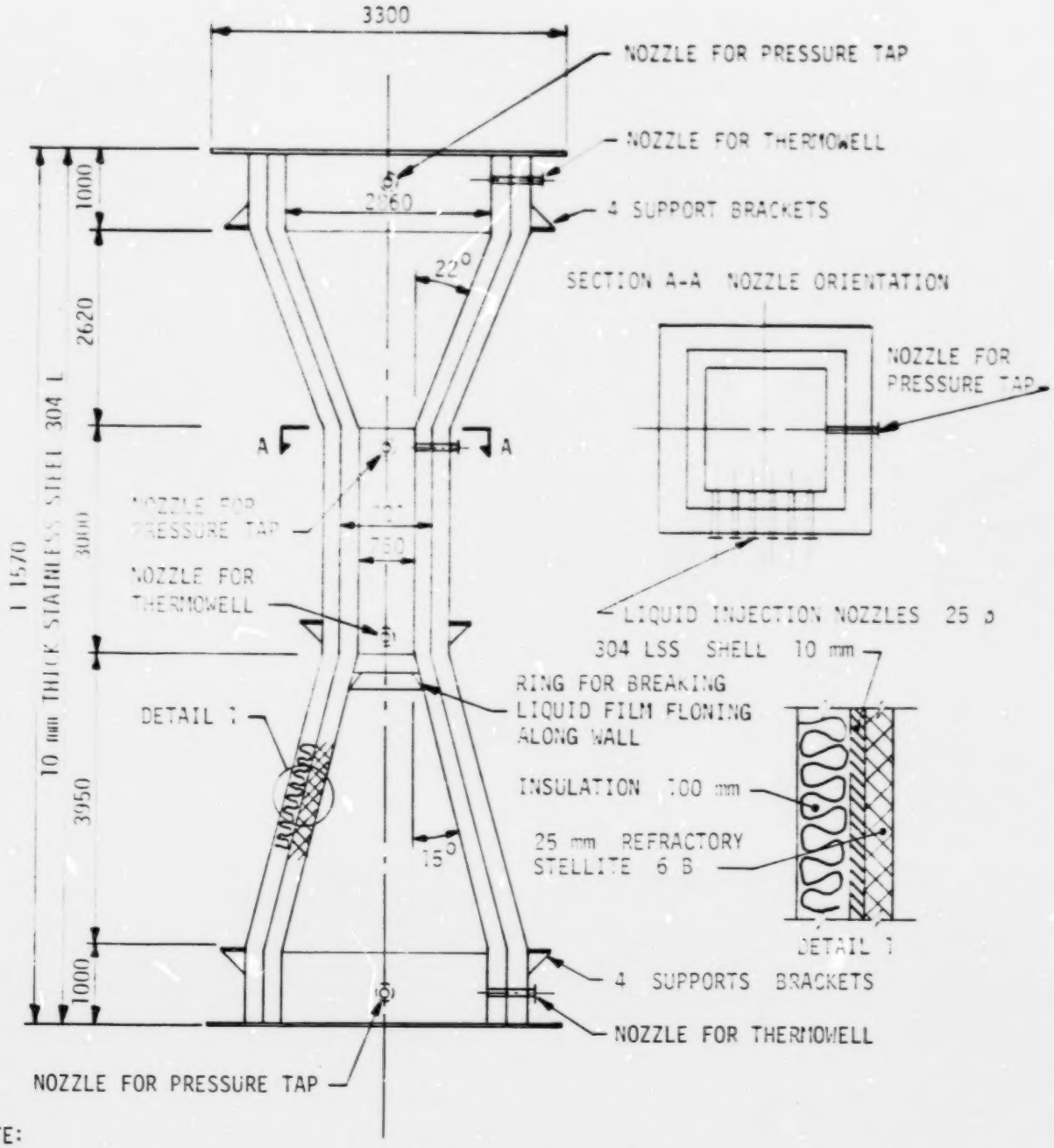
Page/Sheet 10 De/Of 10

Contr 6615 | Subd | Sujet / Subject

Code Coût / Cost Code	Description	Quan	U	Heures-hommes / Manhours U	Total	Coût / Cost	Coût unitaire / Unit Cost Mat'l	C.V. S.C.	Main d'œuvre / Labour	Mat / Equip	Sous-contrat / Sub-contract	Total
	VESSELS (Cont'd)											
	H_2S ABSORBER TOWER 138'(42M) T/T 27'0" 26.24'D approx											
	Fabrication and Erection Labour - Shop & Field, Stress Relief & Test incl. All field welding included	2063k	lbs			6.00			12378000			
	Base Material SS 304 L unit price includes for S/S weld rod supplies.	2063k	lbs			1.80				3712000		
	TOWER SHELL COST								12378000	3712000		16090000
	Tower internals approx 25% of Shell Cost								3092000	928000		4020000
	Material Cost Difference CS. ASTM A517 Gr70 to SS304 L (Tower internals excluded)	2063k	lbs				1.10			<2269000>		<2269000>
	TOTAL - H_2S ABSORBER - Based on Carbon Steel								15470000	2371000		17841000

APPENDIX G

PROCESS DRAWINGS



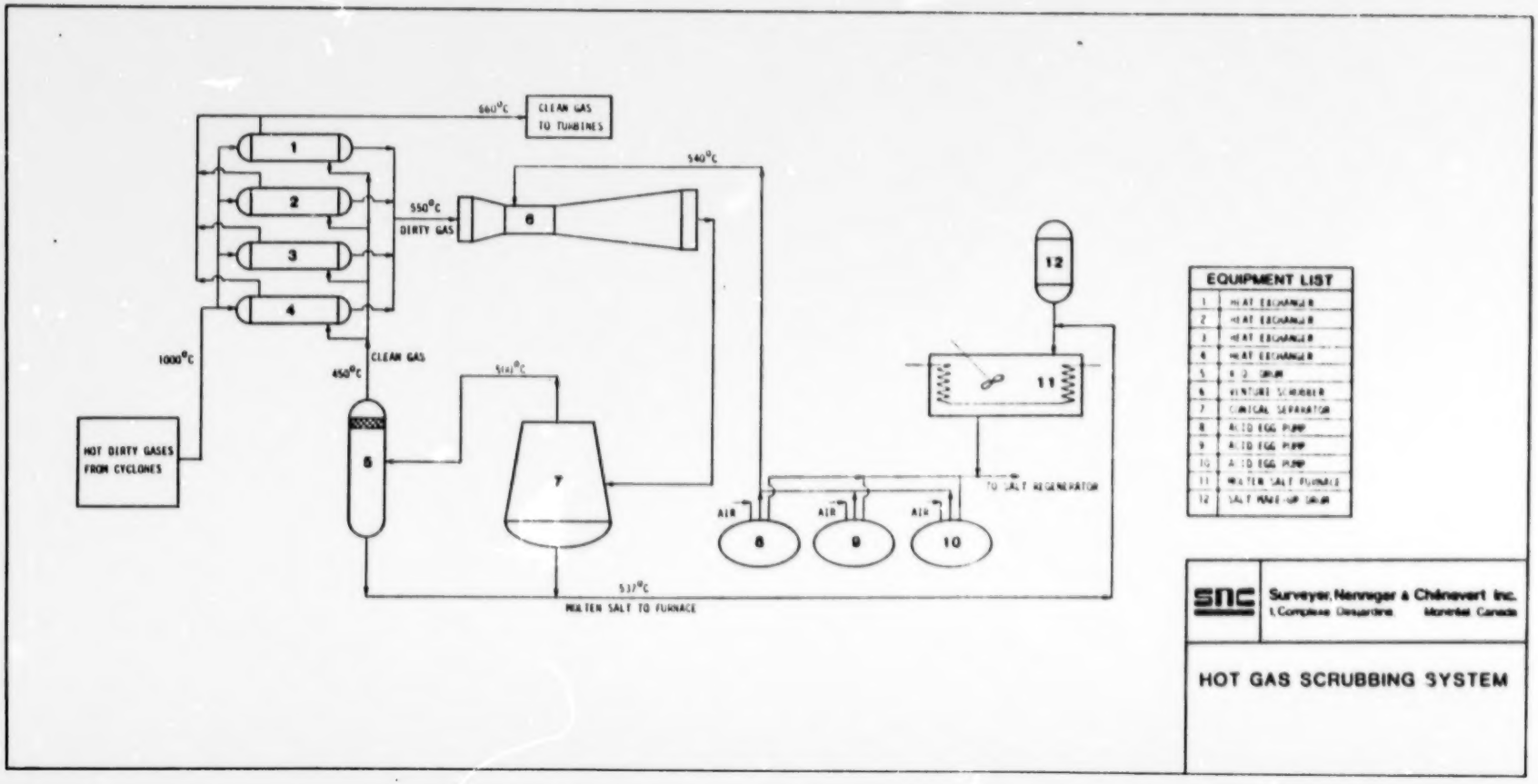
NOTE:

1 MAXIMUM OPERATING TEMPERATURE 750^0 C
2 OPERATING PRESSURE 0.1 MPa
DESIGN PRESSURE 4.0 MPa
3 ALL NOZZLE FLANGES 1050 kPag STD
4 SI UNITS USED THROUGHT

HOT-GAS VENTURI SCRUBBER EMPLOYING MOLTEN SALTS

VENTURI

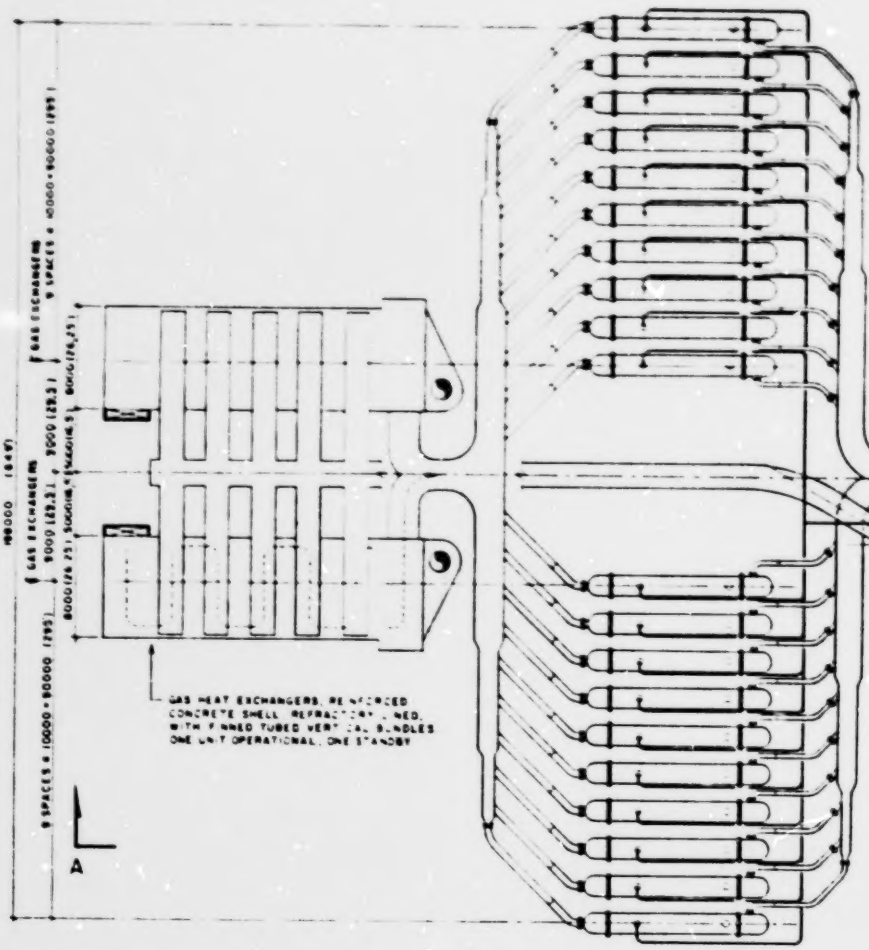
snc



EQUIPMENT LIST	
1	HEAT EXCHANGER
2	HEAT EXCHANGER
3	HEAT EXCHANGER
4	HEAT EXCHANGER
5	K.O. DRUM
6	VENTURI SCRUBBER
7	CONICAL SEPARATOR
8	ACID EGG PUMP
9	ACID EGG PUMP
10	ACID EGG PUMP
11	MOLTEN SALT FURNACE
12	SALT MAKE-UP DRUM

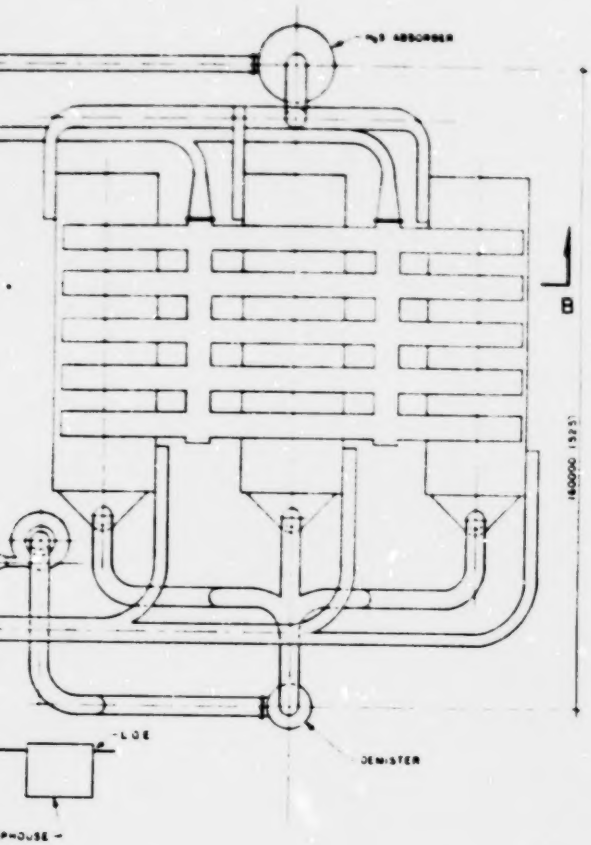
SNC Surveyer, Nenniger & Chênevert Inc.
1, Complexe Desjardins Montréal Canada

HOT GAS SCRUBBING SYSTEM


VENTURI
GAS HEAT EXCHANGERS, REINFORCED CONCRETE SHELL REFRACTORY LINED, WITH FINNED TUBED VERTICAL BUNDLES ONE UNIT OPERATIONAL, ONE STANDBY
A
B

PLAN

RECORD OF DRAWING ISSUE								No	REFERENCE DRAWINGS	No	REFERENCE DRAWINGS	No	DATE	REVISIONS
												1		



BY	CHK	APP	No	DATE	REVISIONS	BY	CHK	APP

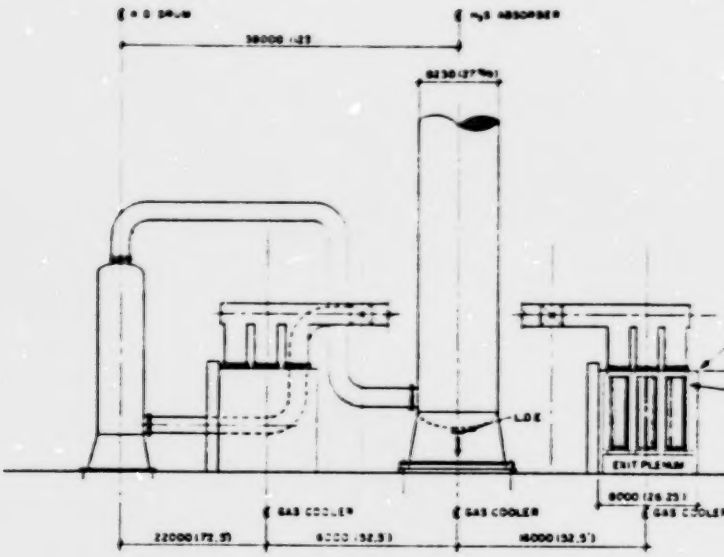
PROFESSIONAL STAMP

SNC Surveyer Nenniger & Chenevert inc.

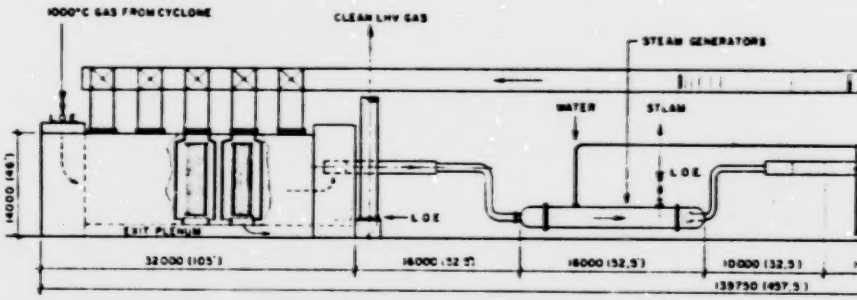
CANMET - ENERGY, MINES AND RESOURCES CANADA

PROJECT: VENTURI GAS SCRUBBERS EMPLOYING MOLTEN SALT

66151000490D 0001 P A



SECTION B-B

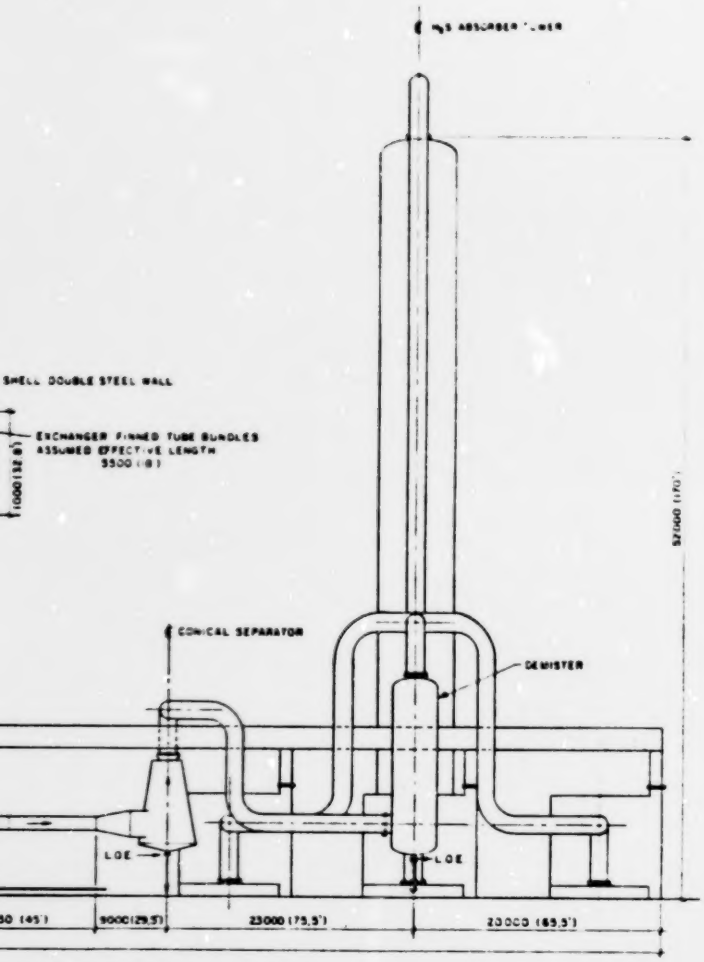


ELEVATION

ISSUE	BY	DATE	STATUS & DESCRIPTION	ISSUE	BY	DATE	STATUS & DESCRIPTION
RECORD OF DRAWING ISSUE							

No	REFERENCE DRAWINGS	No	REFERENCE DRAWINGS

No	DATE
1	



A - A

REVISIONS	BY	CHK	APP	No	DATE	REVISIONS	BY	CHK	APP

PROFESSIONAL STAMP

SNC Surveyer, Nenniger & Chenevert Inc.
1 Complexe Desjardins Montréal Canada

DESIGNED	APPROVED
DRAWN	Project Engineer
CHECKED	Project Engineering Manager
SCALE	Client
DATE	

CLIENT: CANMET - ENERGY, MINES AND RESOURCES CANADA

PROJECT: VENTURI GAS SCRUBBERS EMPLOYING MOLTEN SALT

TITLE:

LOGOS No.	JOB NO.	SHEET No. / No.
6613	10004900	00029 A

APPENDIX H

COMPUTER PROGRAM

APPENDIX H

COMPUTER PROGRAM

A listing of the computer program simulating a venturi scrubber is being separately forwarded to the CANMET Scientific Authority. This program uses the input data given in Appendices A to D. A sample output is also included.

POOR

QUALITY

ORIGINAL